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SYMMETRY OF NORTHERN APPALACHIAN FORELAND FOLDS[1]

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ABSTRACT

The foreland, north and west of the northern Appalachian Mountains, is characterized by gentle folds, trending parallel with the structures of the bordering mountains. Because of regional tilting, the apparent symmetry of these foreland folds is variable and deceptive.

Two methods by which the effects of tilting may be eliminated and the true symmetry of the folds estimated are discussed. It has been found that the northern Appalachian foreland folds are basically asymmetrical, the typical anticlines being about 1.2–1.3 times steeper on the south and east flanks facing the intensely deformed belt.

It is thought that the deformation of this area was caused by tangential stresses from the southeast. The asymmetry of the folds is considered to be controlled by the wedgelike form of the sedimentary cover upon which these stresses acted. The principles developed in this paper may be applicable to other typical forelands.

The foreland of the northern Appalachians, in Pennsylvania and southern New York, lies west and north of the closely folded and faulted Appalachian Mountains from which it is delimited by the structural front (Fig. 1).[2] This foreland area is a broad, gentle, spoon-shaped synclinorium, the lowest part of which is in northwestern West Virginia.

[1] The completion of this study, which was begun in 1930, was made possible by the Eleanor Tatum Long Scholarship in Structural Geology. The writer wishes to express his appreciation to Professor C. M. Nevin, under whose direction the work was carried on, for his many valuable suggestions and his kindly criticism.

[2] Paul H. Price, "The Appalachian Structural Front," *Jour. Geol.*, Vol. XXXIX (1931), pp. 24–44.

The long, and locally sinuous, folds here are approximately parallel to the structural front, and to the axis of the synclinorium. They rise and plunge in domes and saddles along their trend. They appear as gentle undulations of progressively decreasing magnitude, away from the structural front. Although some of the anticlines rise in

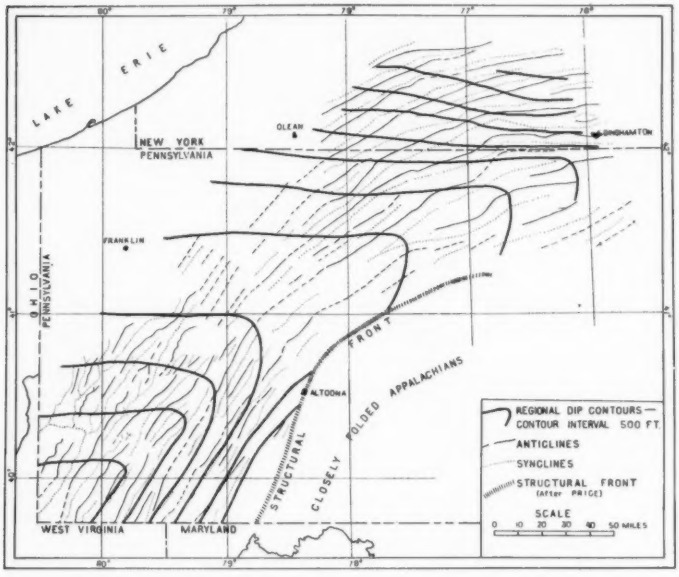

FIG. 1.—Map showing the regional dip of surface formations and the trend of folds in the northern Appalachian foreland. The regional dip contours are not numbered because they cannot be referred to one horizon over the entire area. The contour in the southwestern corner of Pennsylvania is the lowest, however, and if it is numbered 500 (feet above sea level) all the contours, except, perhaps, in New York, represent approximate synclinal elevations of the Pittsburgh coal.

places to heights of 2,500 feet or more above the adjoining synclines, giving average flank dips of some 500 feet per mile, folds 300–800 feet high, with flank dips averaging less than 200 feet per mile, are more numerous.

That the stresses active in forming these foreland folds represent principally the diminishing activity of the deforming thrusts of the

associated mountains is the usual assumption, and this seems justified by their position and characteristics. Less is known, however, of the mode of transmission and application of these stresses.

Largely because of regional tilting, the apparent symmetry of the folds here is deceptive, and has received far less consideration than its importance warrants. They have been described as nearly symmetrical in southwestern Pennsylvania, and as strongly asymmetrical to the southeast in northern Pennsylvania and southern New York. In this they differ from the anticlines of the closely folded mountains, which, with few exceptions, are asymmetrical, and often overturned or overthrust, to the northwest.

The purpose of this paper is to present a study of these folds, emphasizing especially their symmetry, and to suggest causes for some of their characteristics. It is thought that the folds here represent typical foreland structures, and that the principles involved in their formation may have general application.

ESTIMATING THE TRUE SYMMETRY OF A GENTLE FOLD

The term "symmetry," as used in this paper, connotes the general shape of a fold, and is not intended as a term to distinguish whether or not the fold is asymmetrical. If the fold is asymmetrical, and the average dip of the two flanks is known, we may divide the gentler dip into the steeper, and thus obtain a factor which indicates the "degree of asymmetry" of the fold. The "direction of asymmetry" of a gentle anticline is here considered to be the direction in which the steeper limb dips.

If the direction and degree of asymmetry are to have much significance, two sets of factors which predominantly determine the final symmetry of the fold must be considered: (1) All those factors —direction of deforming thrust, mode of transmission of stress, etc., which were instrumental in forming the fold, and which determine what may conveniently be called the "true" symmetry of the fold. (2) Regional tilting, which may accentuate, modify, or reverse the true symmetry of the fold, and impart to it a symmetry which we may speak of as "apparent." In studying gentle folds, the effects of this tilting must be eliminated in order to recognize and appreciate their significant characteristics.

ESTIMATING THE REGIONAL DIP

The general shape of the northern Appalachian foreland after irregularities caused by folding are eliminated is shown in Figure 1. The contours represent the rate and direction of regional dip.

In the preparation of this regional dip map, elevations on key beds in the bottoms of the synclines were taken at numerous points over the area, referred to a common horizon, the Pittsburgh coal, and contoured. For southern New York, the procedure was similar with the exception of the fact that the elevations could not safely be referred to the Pittsburgh coal, so the New York area was contoured separately, using relative synclinal elevations as taken from a map by Wedel.[3] These contours were then generalized to conform with the conditions indicated by areal maps, and known rates of dip, and then tied, as nearly as possible, to the information obtained in Pennsylvania.

The picture of the regional dip thus obtained by contouring synclinal elevations of near-surface key beds is a correct representation of the regional tilting, if it is true that during the folding the anticlines were the controlling elements, and the synclines were neither appreciably depressed nor raised, only as the entire region was titled. Theoretically, "It is reasonable to assume that strata usually, if not universally, bend upward more easily than they can bend downward, because the overlying load may be lifted into the air, whereas the foundation would have to be forced into the globe."[4]

That the rise of the anticlines was the dominant structural feature is further indicated by the fact that the line connecting the bottom of the synclines, on a transverse structure profile of a key bed, is usually a smooth curve, without reversal in direction of slope except as the entire regional dip reverses direction on passing the axial portion of the warping. This is true also for the plains type of fold in the Mid-Continent region, concerning which Clark says, "There

[3] A. A. Wedel, "Geologic Structure of the Devonian Strata of South-Central New York," *N.Y. State Mus. Bull. 294* (1932).

[4] Bailey Willis and Robin Willis, *Geologic Structures*, (2d ed.; New York: McGraw-Hill Book Co., 1929), p. 247.

are virtually no true synclines, in the sense of downwarped folds, but only anticlines and domes raised above the normal monocline."[5]

On the other hand, the synclines often rise and fall in saddles and basins. Some of these basins probably represent actual depression of a part of the syncline, as is indicated by occasional reversals of the syncline-to-syncline surface. Such occurrences are not uncommon in the more strongly folded portions of the area, and necessitate local "smoothing" of the contours.

MODIFICATION OF FLANK DIPS BY REGIONAL TILTING

Obviously, if a folded area is tilted, the average flank dip of any particular anticline will be increased on the side which is dipping in the general direction of the tilt, and decreased on the opposite side. In areas of steep regional tilting and low folds, as in south-central New York, this effect may be sufficient to reverse the true symmetry; or, if the tilt is in an opposite direction, the fold may appear to be extremely asymmetrical.

MODIFICATION OF FLANK LENGTHS BY REGIONAL TILTING

The horizontal component of the distance between the crest of an anticline and the trough of an adjoining syncline may, for convenience, be called the "flank length." This can be scaled directly from a structure map, and used in computing average dips, or in estimating true symmetry.

Since the crests and troughs are points of reversal of dip on curved surfaces, some migration of these points accompanies a regional tilting which is transverse, or diagonal, to the trend of the folds. This migration increases the flank lengths on one side of the folds, and decreases them on the other. If, then, an estimate of true symmetry is to be based upon calculations in which flank lengths are involved, it must be determined whether or not this migration is of sufficient magnitude to vitiate the conclusions. The actual amount of migration for any particular fold along a given section may be closely estimated from an accurate structural profile by drawing, on this profile, inclined lines having the same slope as the regional dip. The true crest and troughs lie where these lines are tangent to

[5] Stuart K. Clark, "The Mechanics of the Plains-Type Folds of the Mid-Continent Area," *Jour. Geol.*, Vol. XL (1932), p. 47.

the high and low points of this profile. Reasonable exaggeration of the profile does not affect the results, because the regional dip is also exaggerated. This procedure enables one to form a picture of the fold in an untilted attitude.

An example of extreme shifting of crest and trough, because of tilting, is shown in Figure 2, which represents a profile of low, northeast-southwest trending folds on a strong, northwest regional dip. The migration here is extreme, because the regional dip transverse

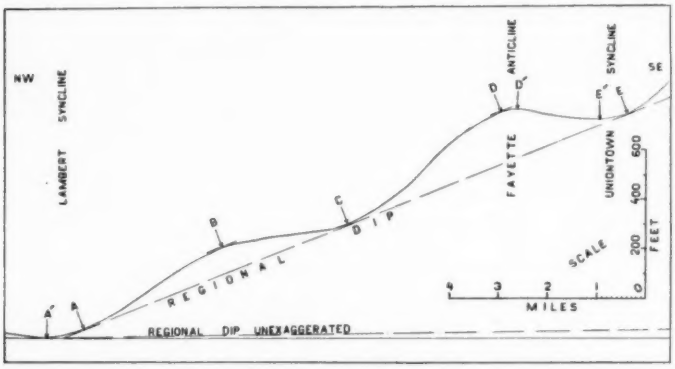

FIG. 2.—NW.–SE. structural profile on the Pittsburgh coal in Monongalia County, W.Va. Exaggerated about 25 times to show the effect of tilting on folds, the average flank dip of which is of the same order of magnitude as the regional dip transverse to the fold. *A′*, *D′*, and *E′* are the points of reversal of dip through which the anticlinal and synclinal axes are drawn on the structure map. *A*, *D*, and *E* locate the reversals of dip as they would be had regional tilting not affected the area. At *B* is the crest of an anticline, and at *C* the trough of a syncline, which, by tilting, have been converted into areas of steepened and flattened dips, respectively. The net results of this tilting are that the anticline at *D* appears, on the structural contour map, to have an extremely long west flank (*D′–A′*) and a very short southeast flank (*D′–E′*). (Drawn from structure map by R. V. Henneen and D. B. Reger: "Monongalia, Marion and Taylor Counties, W.Va.," *W.Va. Geol. Survey*, 1913.)

to the low folds is about 80 feet per mile, and this is nearly equal to the average flank dip of the folds.

The actual amount of migration in any particular case depends largely upon: (1) Steepness of the regional dip transverse to the folds. Other things being equal, migration increases rapidly as the regional dip becomes steeper. (2) The shape, or contour, of the

crest or trough of the fold. As the average flank dip of the fold increases, the curvature becomes more acute and the migration decreases. Combining the preceding factors, it may be said that migration decreases as there is an increase in the ratio of average flank dip to regional dip. In areas where this ratio exceeds some minimum value, the migration, of the typical fold, is so small that uncorrected flank lengths may be used in estimating the symmetry of the structure.

To determine this minimum value for the northern Appalachian foreland folds, a series of accurate profiles, of folds with various heights and widths, in areas of steep and of gentle regional dip, were drawn and the migration estimated. It was found that when the average flank dip is five or six times the regional dip it is difficult to detect any migration, and, when this ratio is about three or four, the migration of any crest or trough is seldom over a few hundred feet. The crests and troughs of gentle folds cannot ordinarily be located in the field closer than a few hundred feet. It is concluded, therefore, that in areas where the anticlines have average flank dips as steep as three or four times the regional dip transverse to the folds, the amount of migration is so small that conclusions based on calculations which involve uncorrected flank lengths are sufficiently accurate. If, however, the average flank dip and the regional dip are about equal (Fig. 2), results based on uncorrected flank lengths are usually erroneous. These conclusions may now be applied to different parts of the area under consideration.

In southwestern Pennsylvania, the regional dip transverse to the folds is very low, with the exception of the southeastern part near and west of the structural front (Fig. 1). In this latter area, however, the regional tilting is about 50 feet per mile. That the flank lengths have not been materially modified by the tilting, is indicated by the average flank dip of the folds here, which, in most places, is as much as 200 feet per mile (four times the regional dip). That the average flank dips here are mostly as steep as this, or steeper, follows from the fact that the anticlines, which average about 8 miles in width, are typically 800 feet high, or higher (Fig. 3). This conclusion is not invalidated by the fact that the anticlines may vary in width from about 4 to 12 miles, because they also vary in height from about 400

to 2,500 feet, and the wider anticlines are the higher. Folds exceptionally wide and, at the same time, low, in comparison with the average, seem not to be present.

In south-central New York, on the other hand, the southwesterly regional dip, of 50–60 feet per mile, is of the same order of magnitude as would be the average flank dip of the anticlines had tilting

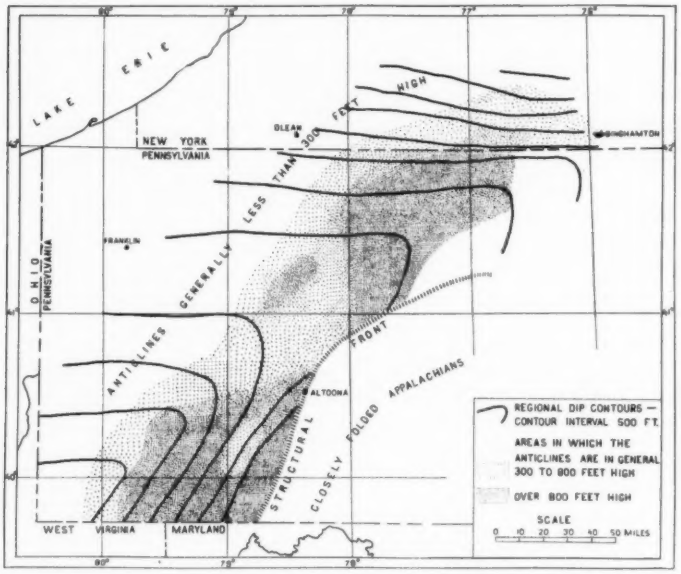

FIG. 3.—Map showing the approximate height of anticlines and the regional dip of surface formations in the northern Appalachian foreland.

not occurred. This is indicated by an average height of less than 500 feet for the anticlines, and, on the map prepared by Wedel,[6] by the fact that the north flanks of the anticlines, in many places, are little more than terraces, whereas the south flanks are steep. The situation here is comparable, therefore, to that pictured in Figure 2, where crest and trough migration has materially modified the flank lengths.

Two other possible sources of error, in calculations based on flank

[6] Op. cit.

lengths, must not be overlooked: (1) The flank lengths should really be scaled on the regional-dip surface, rather than on a flat map. (2) The flank lengths are measured between crest and trough, which, as usually located, are on different horizons. The magnitude and effect of error resulting from these causes has been calculated for several folds, where they would be at a maximum, and have been found to be negligible.

METHODS USED IN ESTIMATING THE TRUE SYMMETRY OF NORTHERN APPALACHIAN FORELAND FOLDS

In the present study, two methods were used in estimating the true symmetry of the anticlines: (1) the average-flank-dip method and (2) the flank-length method.

In discussing these two methods it will be assumed that the migration of the crests and troughs, which accompanied tilting, was insufficient to vitiate conclusions based on uncorrected flank lengths. Actually, this must be established, or the flank lengths must be corrected wherever these methods are applied.

The average-flank-dip method.—If the structure is represented by contours, the present average dip along a selected transverse section is easily calculated for either flank of an anticline. To do this, the difference in elevation of the key bed, on the crest and in the trough of the adjoining syncline, is divided by the flank length along the selected section. To proceed from this to an estimate of the true symmetry involves adding the component of the regional dip, in the direction of the selected transverse section, to the average dip of one flank, and subtracting it from the other. The degree of asymmetry is then obtained by dividing the calculated dips of the two flanks. Having thus determined the true asymmetry of the anticline along a number of typical sections, the true symmetry of the fold as a whole may be estimated.

This method was used frequently in southern Pennsylvania, but cannot be used in northern Pennsylvania and southern New York, except locally, until more information is secured.

The flank-length method.—If regional dip is the general attitude of a syncline-to-syncline surface, it follows that the synclines, bordering any particular anticline, have the same elevation wherever the re-

gional dip is zero. The total dip, from crest to trough, on one limb of an anticline in such an area is the same as that on the other regardless of whether the anticline is symmetrical or asymmetrical. If the flank length on one side of this anticline is less than that on the other, the average rate of dip will be greater on the side of shorter flank length, and the fold is truly asymmetrical. Furthermore, the same estimate of the degree of asymmetry will be obtained by dividing the flank length on the steeper-dip side (short flank) into that on the gentler-dip side (long flank) as would be obtained by the average-flank-dip method. This estimate is not affected by gentle regional tilting, provided the crest and trough migration is not excessive.

The flank-length method is applicable to a considerable portion of northern Pennsylvania where the true symmetry would otherwise be difficult to estimate.

SYMMETRY OF NORTHERN APPALACHIAN FORELAND FOLDS

The symmetry of the folds was studied for that part of the Appalachian foreland which extends north and east from West Virginia into south-central New York (Fig. 1). Though the structural front forms the "inner," or southeastern, boundary of the foreland, the "outer" limit is indefinite. It was found, however, that in most places, where the height of the anticlines is less than 300 feet, the folds are so irregular in trend and symmetry and so readily affected by cross folding, etc., that conclusions based on their study are not reliable. For this reason, the northwestern boundary of the area was delimited by a belt in which the anticlines are in general less than 300 feet high (Fig. 3).

Within the zone of typical foreland folds, branching and irregular bending of the axes, "dying out," cross-disturbances, etc., occur locally. These local areas were not considered in estimating the typical symmetry of the folds for the same reasons that the outer belt of low, irregular undulations was excluded. It is thought that the symmetry of the folds in those places where they are trending fairly straight and regular is more significant than a general average which would include all the undulations present.

For further discussion, it is convenient to consider the southwest-

ern Pennsylvania part of the foreland separately from that which lies in south-central New York and northern Pennsylvania, the division line falling approximately along 41° latitude (Fig. 1).

SOUTHWESTERN PENNSYLVANIA

Detailed structural contour maps are available for most of West Virginia and southwestern Pennsylvania. They have been assembled and discussed, as the Pittsburgh-Huntington Basin, by Richardson.[7] Concerning the shape of the folds, he says that, "unlike most of the folds of the bordering Appalachian Valley Province, many of which have axial planes that dip to the east and steeper dips on their western flanks, the secondary folds of the Pittsburgh-Huntington Basin are in general symmetrical." Calculation of average flank dips of the folds as represented on contour maps corroborates this statement in that, usually, the average flank dips are today equal or nearly equal. Consideration of the fact that the folds, over a considerable part of this area, are on a strong, northwest regional dip (Fig. 1) suggests, however, that the anticlines may be truly steeper to the southeast, and that the apparent symmetry is largely the result of regional tilting.

To test this probability, transverse profiles were drawn in several places across the foreland. From these the true shape of the anticlines was estimated by the average-flank-dip method. For further test, flank lengths were measured at closely spaced intervals across all the folds, and from these the true symmetry estimated. That uncorrected flank lengths may be thus employed here has been previously noted in this paper (p. 231), and is further indicated by the fact that estimates of the true symmetry, as thus obtained here, agree closely with those of nearby areas in which the regional dip is practically zero and could not have caused migration. In addition, wherever the use of uncorrected flank lengths appeared at all doubtful, accurate profiles were drawn and the true symmetry verified. Thus, by the flank-length and the average-flank-dip methods, the symmetry of all the anticlines in that part of southwestern Pennsylvania which is shaded in Figure 3 was estimated.

Average flank-dip calculations were made at 25 places, and flank

[7] G. B. Richardson, "Structure-Contour Map of the Pittsburgh-Huntington Basin" *Geol. Soc. Amer. Bull.*, Vol. XXXIX (1928), pp. 543–52.

length ratios at 51 additional places, making a total of 76 measurements across 11 anticlines. As nearly as possible, the measurements were taken at regularly spaced intervals along the folds.

At 65 of the 76 places tested the anticlines are truly asymmetrical with the southeast flank the steeper; at only 7 are they steeper on the northwest flank; and at 4 they appear to be truly symmetrical. Every anticline appears to be slightly steeper on the southeast flank, after the effect of regional tilting is eliminated, although at exceptional places along them the reverse may be true. Concerning the degree of asymmetry, it was found that the anticlines vary from 1.1 to about 1.8 times as steep on the southeast flanks as on the northwest, being rarely over 1.5 and averaging slightly less than 1.3.

NORTHERN PENNSYLVANIA AND SOUTH-CENTRAL NEW YORK

Detailed structure maps covering northern Pennsylvania and south-central New York are not available, and they would be difficult to prepare because of the usual absence of good key beds. The location, trend, and general character of the folds are well known, however, from the maps and descriptions of Cathcart[8]; Torrey, Fralich, Young, Brewer, and Phillippi;[9] Wedel;[10] and others.

All the descriptions agree in stating that the anticlines are much steeper on the southeast flanks, and that local areas or belts of excessively steep dip, or of faulting, are commonly present on the south flanks. This applies particularly to the folds east of 78° longitude. Less is known of the structure between 78° and 79° longitude south to 41° latitude.

As is shown in Figure 1, the regional dip is rather steep to the south, over a considerable part of this area, especially in south-central New York. This regional tilting must have contributed to the steepness of the south flanks, and must be considered in estimating the true shape of the folds.

Data for the construction of accurate profiles across the folds are

[8] S. H. Cathcart, "Pa. Topo. and Geol. Surv.," parts of *Bull. 102* (1931) and *Bull. 105* (1932).

[9] Paul D. Torrey, C. E. Fralich, W. H. Young, Jr., C. E. Brewer, Jr., and P. M. Phillippi, "Geology of New York and Northern Pennsylvania," *Amer. Petr. Inst. Paper No. 826—4A* (1932).

[10] *Op. cit.*

not available, except in a few places. From the map, Figure 3, however, it is seen that south of the New York state line the height of the anticlines, as nearly as can be estimated, is sufficiently great that it seems safe to use uncorrected flank lengths in estimating the symmetry of the folds. Especially is this true where the anticlines are high and the regional dip low, which is the relation over a large part of the area. Furthermore, the regional dip is diagonal to the folds, and hence only a component of the regional tilting was effective in causing crest and trough migration. The symmetry of the folds in northern Pennsylvania was estimated principally, therefore, by the flank-length method.

These flank lengths were scaled directly from the published structure maps showing the locations of anticlinal and synclinal axes, additional field work being done in those parts of the area where recent maps have not been published. Though these maps are probably less accurate than those in southwestern Pennsylvania, especially in the location of the synclines, the results obtained are believed to represent a close approach to a true picture of the symmetry of the folds. Flank-length ratios were calculated at 60 places scattered across 9 anticlines in Pennsylvania northeast of 41° latitude. Some of these anticlines are direct continuations of folds studied in southwestern Pennsylvania.

Of the 60 places tested, at 8 the anticlines appear to be slightly steeper to the northwest, at 6 symmetrical, and at 46 asymmetrical to the southeast. With one exception, all the anticlines appear to be steeper to the southeast, after the effects of regional tilting are eliminated. This exception is the Wellsboro anticline, which appears to have a shorter northwest flank in as many places as it has a shorter southeast flank.

All the other anticlines of northern Pennsylvania are comparable in degree of asymmetry to those in southwestern Pennsylvania. They vary from 1.1 to about 2.0 times steeper on the southeast flank, being in most cases less than 1.6, and averaging slightly over 1.3. They apparently differ from the southwestern Pennsylvania folds, however, by having local areas of excessively steep dips on the south flanks.

These steep dips are known to increase with depth and, in some

cases at least, to overlie faults. Failure to note locally steepened dips in southwestern Pennsylvania may be due, in part at least, to the fact that there the surface formations on the flanks of the folds are usually several hundred to a thousand or more feet stratigraphically above the surface formations in northern Pennsylvania.

As already noted, such extensive crest and trough migration has occurred in south-central New York that the use of uncorrected flank lengths is not permissible in estimating true symmetry. The north flanks of the anticlines here are in general shorter than the south, due, no doubt, to the tilting.

The following two lines of evidence indicate that these anticlines are truly, as well as apparently, steeper on the south flanks, and, therefore, similar in symmetry to other northern Appalachian foreland folds: (1) Local areas of abnormally steep dip, or of faulting, on the south flanks of the anticlines occur in southern New York, just as in the stronger folds of northern Pennsylvania. A good example of this is the south flank of the Alpine anticline near Ithaca. (2) In parts of the area—for instance, near Elmira, Corning, and Spencer, where the folds are higher and the regional dip somewhat lower—the anticlines have shorter south flanks. This indicates that here the curvature of these folds is so acute that the regional tilting has not reversed the true relative flank lengths.

FOLDS OF OTHER FORELANDS

A rapid survey of several other regions suggests that anticlines asymmetrical toward the closely folded mountains are not confined to the Appalachians, and that this may be the characteristic shape of foreland folds in general.

North of the Ouachita Mountains, in Arkansas and Oklahoma, is the foreland area of the Arkansas Valley synclinorium. The deformation in this zone diminishes northward. Concerning the symmetry of the folds in Arkansas, Croneis says that "most of the anticlines south of the Arkansas River are steeper on their north flanks, but those north of the river are steeper on their south flanks."[11] This may be caused partly by regional tilting, but the detailed data

[11] Carey Croneis, "Geology of the Arkansas Paleozoic Area," *Ark. Geol. Surv. Bull. 3* (1930), p. xviii.

necessary to test this possibility are lacking. On the contrary, the asymmetry to the south of certain anticlines, notably those of Sequoyah County, in the Oklahoma part of the foreland[12] cannot be caused by regional tilting, because the regional dip is to the northwest. Apparently the Ouachita foreland folds are similar in symmetry to those of the Appalachians.

The foreland zone east of the Rocky Mountains differs strikingly from that of the Appalachians. Instead of the typically gentle, long, and sinuous folds, paralleling the trend of the mountains, the folds here are more deformed and appear as elongated domes and anticlines, trending in various directions. In many places, especially in Wyoming, these folds occur in intermontane basins. Laccolithic intrusions and buried fault blocks have probably affected the shapes of the folds locally. An extensive study of the local structural and stratigraphic conditions would be required before comparing the symmetry here with that of the Appalachians. Asymmetries in different directions occur here, and the drawing of general conclusions from selected scattered folds is not permissible.

North of the Alps the structures are in many ways similar to those east of the Rocky Mountains. Thrust sheets have, to a considerable extent, overridden the Alpine foreland. Resistant massifs, block-faulted areas, and belts of pre-Alpine folding are present in Central Europe. Stille's study suggests, however, that the symmetry of the structures here is similar to that of the Appalachian foreland folds. For example, in describing the symmetry of the structures in Spain, he says:

> The strong asymmetries of the mountain chains of Alpine type toward the Celt-Iberian foreland are contrasted with more subdued asymmetries within the Celt-Iberian block toward the fringing folded mountain chains.[13]

It is also noteworthy that Stille concludes:

> It has been recognized that in Spain and middle Europe, not only certain local asymmetries, but even entire groups of them are compatible with the structural behavior of what is termed a foreland. The writer is inclined to think that

[12] J. A. Stone and C. A. Cooper, "Haskell, Latimer, Leflore and Sequoyah Counties, Oklahoma," *Okla. Geol. Surv. Bull. 40*, Vol. III (1930).

[13] Hans Stille, "Asymmetric Folds with Reference to German Salt Bodies," *Bull. Amer. Assoc. Petr. Geol.*, Vol. XVI (1932), p. 173.

this point may be of some significance also for the analysis and understanding of some foldings in America.[14]

ORIGIN OF NORTHERN APPALACHIAN FORELAND FOLDS AND FACTORS DETERMINING THEIR SYMMETRY

An attempt to explain the symmetry of the folds bordering the northern Appalachian Mountains must take into consideration their origin, and the stratigraphic and structural setting in which they were formed. Discussion of the general theory of mountain deformation will be limited, however, to those factors which, it is thought, apply directly to the symmetry of the foreland folds.

THE FORELAND WEDGE OF SEDIMENTS

The fact that the intense folding and faulting of the Appalachian Mountains occurred where great thicknesses of sediments had accumulated in a former geosyncline has long been recognized. It is also well known that the more gently folded, bordering zone corresponds in position with a wedgelike thinning out of sediments away from the deepest parts of the geosyncline. The general form of the upper part of this wedge of sediments—that part which is included between the Lower Silurian and the Lower Pennsylvanian—is shown by contours in Figure 4. That the formations, especially in the Upper Devonian, thicken rapidly toward the closely folded mountains is an important fact.

At the time of the deposition of the Pottsville, the top of the Medina must have been dipping southeast at an average rate of about 55 feet per mile. Locally, in southern Pennsylvania, the regional inclination of the top of the Medina appears to have been somewhat higher—about 70–80 feet per mile. East of 78° longitude, the limited data indicate a lower rate of dip. No doubt thickening occurs in the Medina and other deeper formations also. It seems reasonably certain, therefore, that late in the Paleozoic the deeplying competent limestones and the Basement Complex had a southeastward regional dip of the order of magnitude of 60–80 feet per mile. In the writer's opinion, this was of fundamental importance in determining the symmetry of the foreland folds. Before discussing this further, however, it is necessary to consider the possi-

[14] *Ibid.*, p. 174.

bility that flowage of the sediments was the principal cause of the deformation.

THE FLOWAGE AND GLIDING THEORIES

Under the conditions pictured above, a tendency for the sediments to flow, under the force of gravity, into the deepest parts of the basin probably existed. The importance of such a flowage and gliding tendency has been urged by Haarmann,[15] Bain,[16] and others

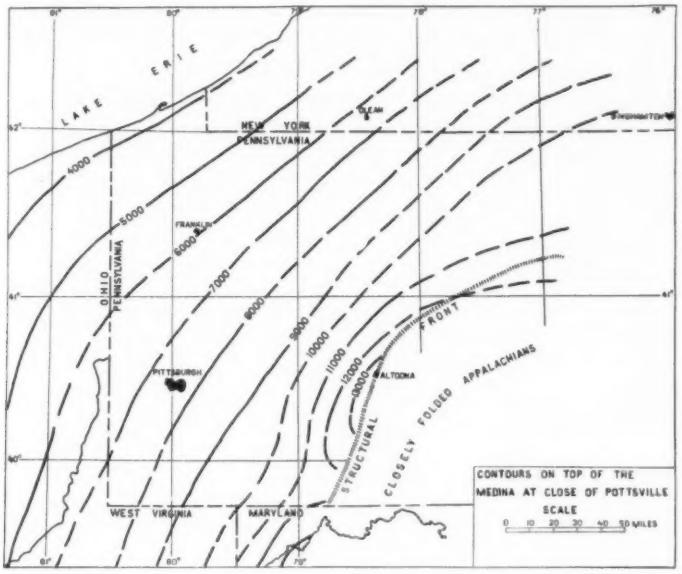

FIG. 4.—Convergence map of the Pottsville-Medina interval. Considering that the top of the Pottsville was horizontal when deposited, the contours represent, by depths below sea level, the southeast regional dip of the Medina at the close of the Pottsville.

who consider it, in one form or another, an important factor in causing mountain folding.

That the major deformation of the Appalachian foreland originated in this manner seems, to the writer, very improbable. Although

[15] E. Haarmann, *Die Oszillationstheorie, eine Erklärung der Krustenbewegungen von Erde und Mond* (Stuttgart, 1930).

[16] G. W. Bain, "Flowage Folding," *Amer. Jour. Sci.*, Vol. XXII, ser. V (1931), pp. 503–30.

the anticlines here are mostly steeper on the southeast, as, according to Bain's criteria,[17] they should be if caused by flowage, the following considerations indicate that this process was not the principal factor in deforming this area.

Flowage to the southeast, in the foreland, would result in extensive tension effects in the formations on the upper part of the slope to the northwest. Few indications of tension have been noted.

It is true, however, that the total shortening involved in the folding here was not great. Ashley[18] estimated that the total shortening involved in folding the surface formations, along a line from the Allegheny Front northwestward through Punxsutawney, Pennsylvania, was less than 30 feet. The writer made similar calculations along several lines across the foreland of Pennsylvania, and arrived at estimates varying from 50 to 1,000 feet, depending upon the intensity of the folding. The greatest shortening estimated was in extreme southern Pennsylvania.

On the outer part of the foreland, a few high-angle normal faults are known. In opposite sections where the shortening is several hundred or a thousand feet, however, the apparent absence of very extensive tension effects is difficult to explain satisfactorily, if active flowage is assumed.

Two arguments against explaining the intense folding and faulting of the Appalachians by Haarman's gliding theory are summarized by Longwell as follows:

> Since the overturning and overthrusting is toward the west-northwest, according to Haarman's conception the sediments (of the mountain belt) glided westward from a region of uplift near the present Atlantic coast. In this event, however, we would expect to find the most severe deformation toward the west side of the folded tract, with a conspicuous decrease in intensity toward the east. Exactly the opposite is true, throughout the length of the chain. Moreover it is hard to reconcile with Haarman's views the occurrence of great thrusts in which the crystalline basement rocks are thrust over the folded sediments. Such thrusts are present in the Appalachians, the Scottish Highlands and other mountain zones.[19]

[17] *Ibid.*

[18] G. H. Ashley, "Structure (of Southwest Pennsylvania)," *Report of the Topo. and Geol. Surv. Commission of Pa.* (1906–8), p. 216.

[19] C. R. Longwell, "The 'Oscillation Theory' of Diastrophism (Discussion)," *Amer. Jour. Sci.*, Vol. XX, ser. V (1930), p. 220.

The same arguments apply to the flowage theories, and to assume that the foreland structures were caused by flowage or gliding, but that the deformation of the mountain zone was not, would not seem to be justified.

It is concluded, therefore, that flowage and gliding were not the principal causes of the deformation of the Appalachian foreland. The more widely accepted theory that this deformation and that of the adjoining mountains is the result of directed tangential stresses seems to explain more fully the facts. It is thought, however, that a tendency for flowage to the southeast here was one factor, though perhaps a minor one, in determining the shape of the folds.

DIRECTION OF THE TANGENTIAL STRESSES IN THE FORELAND

The reverse faults, apparently overthrust to the northwest, and the northwestward decrease in the intensity of deformation have often been cited as evidence that the Appalachian Mountain thrusts were directed from the southeast. It is rather generally assumed that the thrusts in the bordering zone of gentler folding were also directed from the southeast and represent a "dying out" of the mountain deforming stresses. The fact that the northwestward decrease in the intensity of folding continues, though not in a regularly graded procession, across the foreland is the principal evidence that this assumption is correct.

Chamberlin, however, considers the possibility that, although in the western portion of the mountain belt the active movement was from the southeast, in the foreland stresses of less intensity were directed toward the mountains.[20] He also suggests:

> If this foreland region was crowded inward toward the mountains to a slight extent, this might readily explain the asymmetry of these gentle folds. The upper strata would naturally shear to a slight extent over the deeper strata which were less movable and this would give a slight tendency of overturning of the anticlines toward the southeast just as they are found.[21]

If the direction of stress was the only, or even the controlling factor in determining the asymmetry here, it seems that a correlation should exist between the intensity of folding and the degree of asym-

[20] Rollin T. Chamberlin, "Isostasy from the Geological Point of View," *Jour. Geol.*, Vol. XXXIX (1931), pp. 19–22.

[21] Personal communication.

metry of these gentle folds. Actually, this asymmetry is about the same in the zone of mild folding on the west and north as in the larger folds of the foreland to the east and south. Partly for this reason, it is concluded that this asymmetry was controlled largely by the wedgelike form of the sediments, and gives little, if any, indication as to the direction of the deforming stresses.

EFFECTS OF THE WEDGE OF SEDIMENTS

In the following discussion of the effects of the wedge of sediments it is thought that the stresses here were directed from the southeast. This direction of stress is assumed largely because of the outward decrease in the severity of deformation. Though the manner in which the wedge influenced the symmetry of the folds is more evident when the stress is thought of as directed toward the northwest, it should be noted that the same factors would have operated in a similar manner had the thrusts acted in the opposite direction. In the latter event, however, the shearing tendency mentioned by Chamberlin[22] would have introduced an additional factor, the relative importance of which is difficult to estimate.

Obliquely-upward rise of anticlines in the wedge.—It is generally considered that the tangential stresses which deformed the northern Appalachian region must have been transmitted largely through the Cambro-Ordovician limestones and the Basement Complex. The thick, overlying sedimentary section, consisting predominantly of shale and sandstone, seems entirely incompetent to transmit deforming stresses over the distance involved. Therefore, in the foreland, the thrust is thought of as transmitted up a regional slope of from 60 to 80 feet per mile, i.e., the initial dip.

Assuming that rising of the anticlines was the dominant feature in the deformation, a tendency would exist for the direction of this rise to dip to the northwest rather than to be propagated vertically. This results partly from the fact that the lifting component on an inclined competent plane is essentially perpendicular to that plane, and partly from the tendency for the overlying incompetent sediments to flow to the southeast; it is not dependent upon the direction of the causal stress. The anticlines, then, rose obliquely rather than directly upward.

[22] *Ibid.*

This conclusion is supported by the attitude of the axial plane of the usual northern Appalachian foreland anticline when the effect of regional tilting is eliminated. The hade, to the northwest of the axial plane for the usual surface fold of southern Pennsylvania—about 8 miles wide and 1.3 times as steep on the southeast as on the northwest flank—is of the same order of magnitude as the initial regional dip (to the southeast) of the underlying competent beds. In other words, a plane, bisecting the limbs of the typical foreland-surface anticline of southern Pennsylvania, is approximately perpendicular to the underlying competent limestones and Basement Complex.

It has often been assumed that these anticlines rose in an essentially "competent" manner. An adequate discussion of this question, involving as it does a consideration of the stresses in a broad, loaded arch, and the strength of rocks under the conditions existing below the surface, is not possible within the limits of this paper. It is important to note, however, that in studying the Chestnut Ridge arch near Punxsutawney, Pennsylvania, where it is 14 miles wide and 740 feet high, Ashley calculated that, if it were self-supporting, it would exert a tangential thrust of about 290,000 tons per square foot, or about 1,000 times the crushing strength of the materials. Therefore, it must have been supported always from below.[23] Though few of the arches are as wide as 14 miles, the general conclusion that they must at all times have been supported from below can hardly be doubted. This applies equally well to the early stages in most so-called competent anticlines. On the other hand, considerations previously mentioned (pp. 228–29) indicate that rise of the anticlines was the dominant factor in deformation and sinking of the synclines was of relatively minor importance.

Perhaps partial relief of pressure under the "competent" formations induces deep-seated flowage into the arch, to equalize the pressure, and by a continuation of this process the arch rises. A somewhat similar view has been suggested by Ashley.[24] If this be true, the dominant rôle of the "competent" formation is not to raise the

[23] G. H. Ashley, "Studies in Mechanics of Allegheny Structure (Abstract)," *Sci.*, N.S., Vol. XXVII (1908), pp. 924–25.

[24] *Ibid.*

arch, but to transmit the stress, lower the pressure under the arch, and influence the true symmetry of the fold.

Underthrusting tendency because of the wedge.—A consideration of the relative elevations of the initial synclines in the foreland suggests an additional reason why the anticlines are basically steeper on the southeast flanks. The general synclinal area southeast of the usual initial foreland anticline was a few hundred feet lower than the synclinal area northwest of it. This resulted from the southeast initial dip of the lower formations, induced by sinking of the geosyncline. Under these conditions, most of the deep-seated faulting which occurred probably took the form of underthrusts from the southeast. In part this was because overthrusting would have necessitated movement up and over the formations where they were at a higher elevation. Also important, perhaps, was the fact that underthrusting was assisted and overthrusting resisted by the tendency for the incompetent strata to flow southeastward over the competent basement formations, and also by the obliquely upward rise of the anticlines. Here, as in all other cases of possible underthrusting, active downward movement was resisted by the underlying material, and this may have inhibited extensive underthrust movements.

In this connection it is significant to note that deep drilling in northern Pennsylvania has revealed the presence, on the south flanks of some of the anticlines, of extensive high-angle, north-dipping, reverse faults of several hundred feet displacement.[25] Though the general supposition is that these faults represent underthrusts from the south, it has not been possible to determine that actual downward movement of the footwall occurred. Extensive accurate data on synclinal elevations of key beds would probably indicate the answer to this question. It is entirely possible that the major movement was a rise of the hanging walls on the north, induced by the oblique upward rise of the anticlines assisted by the tendency to southward flowage toward the center of the basin.

[25] J. French Robinson, V. Jones, and J. Gaddess, "Sub-surface Structural Geology of the Northern Pennsylvania and Southern New York Gas Fields: 2nd Oil and Gas Conference Proceedings," *State College, Pa., Bull. XI* (1932), pp. 9–18; also Torrey, Fralich, Young, Jr., Brewer, Jr., and Phillippi, *op. cit.*, and Cathcart, *op. cit.*

SUMMARY

The general conclusion that seems justified from this study is that the typical northern Appalachian foreland folds are basically asymmetrical. The anticlines are steeper on the flank facing the more intensely deformed mountains. The folds are mostly gentle, however, and this typical asymmetry is so readily masked by regional tilting and by local factors that many apparent exceptions are encountered. Careful study reveals very few true exceptions.

The evidence indicates that the deformation of this area must be explained in terms of directed tangential stresses. It is suggested that the asymmetry of the foreland folds is primarily a result of the wedgelike form of the sedimentary cover, and that the reason for the asymmetry of the folds is to be found largely in a combination of (1) the obliquely upward rise of the anticlines, (2) underthrusting, and (3) tendency of the sediments to flow into the deepest part of the basin. It is thought that the direction of thrusting in the foreland was from the southeast, but the possibility that it was from the opposite direction, and thus influenced the direction of asymmetry, seems worthy of further study.

That the direction of thickening is an important factor in determining the direction of overturning and reverse faulting in the intensely deformed mountain ranges is also a possibility worthy of additional consideration. The work of Price[26] indicates that, in the late Paleozoic, the deepest part of the Appalachian geosyncline was in the general position of the present structural front. If this is correct, the initial dip of the deep-lying strata of the mountain belt must have been prevailingly westward, and the overturning and overthrusting is in this direction of thickening.

[26] *Op. cit.*

SOME METAMORPHIC EFFECTS OF THE REPUBLIC GRANITE

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ABSTRACT

Extensive contact metamorphism has been produced by the intrusion of a post–Upper Huronian granite into Huronian formations of northern Michigan. Quartzites, dolomites, iron-bearing formations, slates, and graywackes, all have reacted to the intrusion of the granite. Not only have the usual and characteristic contact metamorphic minerals developed, but also certain metasomatic minerals have been formed and some unusual features of contact metamorphism have resulted.

INTRODUCTION

In the northern peninsula of Michigan, forming a part of the Lake Superior pre-Cambrian region, is an area embracing approximately 1,400 square miles which exhibits the features described in this article. The northern limit of this area lies roughly along a line connecting the city of Marquette on the east with the northern part of Lake Michigamme on the west, and its southern end is near the Wisconsin-Michigan boundary. It contains parts of the Marquette, Sturgeon River, and Felch Mountain iron districts.

Almost the entire central part of the area is occupied by granite, much or all of which is thought to be of post–Upper Huronian but pre-Cambrian age.[1] Around the margins of the granite are complexly folded Huronian and horizontal Cambrian rocks. In general the Cambrian formations occur in the eastern part of the area and the Huronian formations along the northern and western margins of the granite, but projections of Huronian rocks extend far into the granite in the southern part of the area.

Metamorphism produced by the granite in this area was mentioned by early writers, as Foster and Whitney,[2] and Wadsworth,[3]

[1] C. A. Lamey, "The Intrusive Relations of the Republic Granite," *Jour. Geol.*, Vol. XLI (1933), pp. 487–500.

[2] J. W. Foster and J. D. Whitney, "Report on the Geology and Topography of the Lake Superior Land District: Part II, The Iron Region, together with the General Geology," *32d Congress, Spec. Sess., Senate Doc.*, Vol. III, No. 4 (1851), pp. 89–100.

[3] M. E. Wadsworth, "Notes on the Geology of the Iron and Copper Districts of

who believed the granite to be younger than at least some of the Huronian formations. Seaman[4] also, although his observations do not appear in published form, long ago recognized the fact that the Huronian formations close to the granite show very marked evidence of contact metamorphism. More recently Van Hise and Leith[5] recognized the possibility of a granite younger than Upper Huronian in the Lake Michigamme area which might have caused some of the metamorphism of the Michigamme formation. These early observations, and some more recent ones by members of the Michigan Geological Survey[6] and by the writer,[7] comprise almost the entire published material regarding contact metamorphism produced by granite in this area, with the exception of the excellent detailed descriptions by Clements[8] of the effects produced in the Upper Huronian Michigamme formation of the Crystal Falls district. It seems desirable, therefore, to describe the contact metamorphism of the Huronian formations somewhat more in detail.

In connection with the following discussion it should be borne in mind that the folding of the Huronian rocks preceded and probably in part accompanied the intrusion of the granite; consequently the rocks had been mashed and their original character changed before contact metamorphism took place, and the metamorphic minerals developed in the Huronian formations are those formed during conditions of stress as well as the usual minerals developed by contact metamorphism and metasomatism. Moreover, because of the thick-

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Lake Superior," *Bull. Mus. Comp. Zoöl.*, Vol. VII (1880); also, "A Sketch of the Geology of the Iron, Gold, and Copper Districts of Michigan," *Rept. State Geologist for 1891–92, Geol. Surv. Mich.* (1893), pp. 61–73.

[4] A. E. Seaman, oral communication.

[5] C. R. Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," *U.S. Geol. Surv. Mono. LII* (1911), p. 268.

[6] L. P. Barrett, F. G. Pardee, and W. Osgood, "Geological Map of Iron County, Michigan," *Geol. Surv. Mich.* (1929); C. O. Swanson, "Report on the Portion of the Marquette Range covered by the Michigan Geological Survey in 1929," *ibid.*

[7] Lamey, "Granite Intrusions in the Huronion Formations of Northern Michigan," *Jour. Geol.*, Vol. XXXIX (1931), pp. 288–95; also "The Intrusive Relations of the Republic Granite," *op. cit.*

[8] W. S. Bayley, J. M. Clements, H. L. Smyth, and C. R. Van Hise, "The Crystal Falls Iron-bearing District of Michigan," *U.S. Geol. Surv. Mono. XXXVI* (1899), pp. 195–98.

ness and irregular distribution of glacial deposits, it is not possible to establish well-defined contact zones, although a marked decrease in metamorphism is to be observed some distance from the granite contact.

HURONIAN FORMATIONS AFFECTED BY CONTACT ACTION

The Huronian formations surrounding the granite may be placed in four rock groups; namely, (1) argillaceous, (2) ferruginous, (3) dolomitic, and (4) arenaceous. These groups are represented by: (1) the Wewe slate, the lower part of the Siamo formation, and the Michigamme slate and graywacke; (2) the upper part of the Siamo formation, the Negaunee iron formation, the Vulcan iron formation, and part of the Bijiki schist; (3) the impure and cherty Kona and Randville dolomites; and (4) the Mesnard, Sturgeon, Ajibik, and Goodrich quartzites. The quartzite formations usually contain argillaceous material in their lower parts. This is especially true of the lower part of the Mesnard formation, much of which is slate and graywacke.

Not all of the Huronian formations show well-marked contact metamorphism, because of their positions with reference to the granite. The formations most strongly affected are the Michigamme, Siamo, Negaunee, Vulcan, Randville, Mesnard, Sturgeon, Ajibik, and Goodrich. Although the Mesnard formation has been much affected by the intrusion of the granite, it will not be considered in the present discussion because of its relation to the origin of the Palmer gneiss, a problem of sufficient importance to warrant separate treatment. Also, only the major features of the metamorphism of the other formations can be presented here.[9]

THE METAMORPHOSED MICHIGAMME FORMATION

The Michigamme formation, where unaffected by contact metamorphism, consists of coarse-grained graywacke and fine-grained slate, with all gradations between these two (Fig. 1). The principal minerals composing these rocks are quartz, chlorite, biotite, altered plagioclase, altered pyroxene, and some white mica, magnetite, epidote, zoisite, and zircon.

[9] A detailed discussion of this subject is presented in a dissertation for the doctorate at Northwestern University, and is contained in "The Intrusive Relations and Metamorphic Effects of the Republic Granite," on file in Deering Library.

In general there are three phases of the metamorphosed formation: (1) an andalusite-bearing schist, (2) a staurolite-garnet schist, and (3) a gneiss, all of which contain tourmaline. The andalusite-bearing schist occurs on small islands in the southern part of Lake Michigamme and at the extreme southern end of the lake, and the other two types of the formation occur in a belt extending along the south side of the west arm of Lake Michigamme and westward for about 2 miles. This belt has a width of about $\frac{1}{2}$ mile, contains many

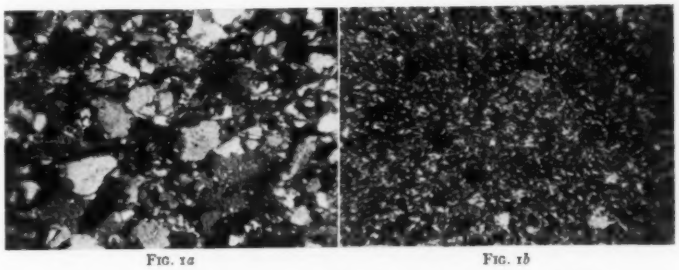


FIG. 1*a* FIG. 1*b*

FIG. 1.—Normal Michigamme formation. Crossed nicols ×22. (*a*) Graywacke, (*b*) slate.

pegmatitic dikelets in its eastern part, and is thought to mark the location of a westward projecting tongue of the Republic granite.[10] The gneissoid phase of the Michigamme formation mostly occurs in the eastern part of this belt, near pegmatitic dikelets.

The andalusite-bearing schist is characterized by an abundance of andalusite, staurolite, and garnet, associated with tourmaline, biotite, muscovite, plagioclase (probably albite), some apatite, and a background of interlocking quartz (Fig. 2). Outcrops of this phase of the Michigamme formation are studded with garnet, peculiar knotty patches of andalusite, and staurolite crystals, some of which attain a length of several inches. Near pegmatitic intrusions composed chiefly of quartz and suggesting the tops of cupolas there are very fresh andalusite crystals several inches long and half an inch across. These crystals occur along the edges of the intrusions and sometimes actually within the quartz.

The character of the staurolite-garnet schist differs from place to

[10] Lamey, "The Intrusive Relations of the Republic Granite," *op. cit.*, pp. 498, 500.

place, and it may grade into a gneiss. Some of the schist is composed chiefly of quartz and biotite, but in many instances it shows a selective development of staurolite and garnet in alternating bands, these minerals being accompanied by quartz, biotite, and tourmaline. With closer approach to pegmatitic dikelets, a white mica may appear, sometimes in parallel position with biotite, associated with tourmaline, apatite, and minute feldspar veinlets, and this rock may

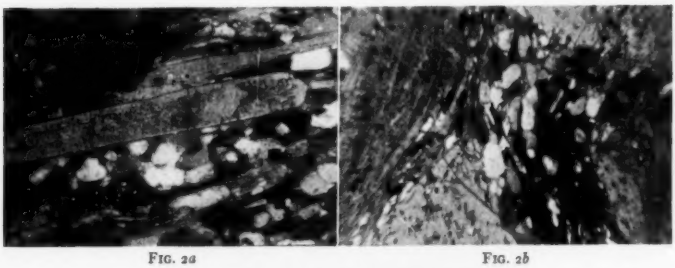


FIG. 2a FIG. 2b

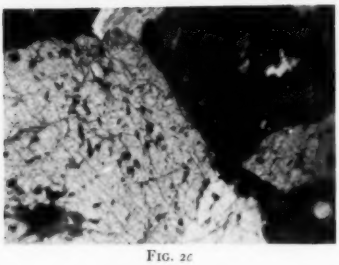


FIG. 2c

FIG. 2.—Andalusite-bearing Michigamme formation. (*a*) Large tourmaline. Crossed nicols ×22. (*b*) Staurolite in large crystals. Crossed nicols ×9. (*c*) Mass of andalusite crystals. Crossed nicols ×9.

in turn grade into one in which white mica and orthoclase occur in parallel orientation, locally accompanied by tourmaline, and in which feldspar dikelets cut across the schistosity, the feldspar becoming interlaminated with white mica along the edges of the dikelet, giving rise to a peculiar gradational boundary (Fig. 3). In some instances the staurolite-garnet schist grades into a gneiss, and may be composed of poikiloblastic amphibole, biotite, muscovite, garnet, tourmaline, apatite, orthoclase, some chloritoid, and quartz, or it

may lack amphibole and contain chiefly quartz, feldspar, chlorite, white mica, some biotite and some apatite (Fig. 4).

METAMORPHISM OF FERRUGINOUS ROCKS

Around the margins of the Republic granite where it approaches the ferruginous rocks of the area there is a belt of strong magnetic

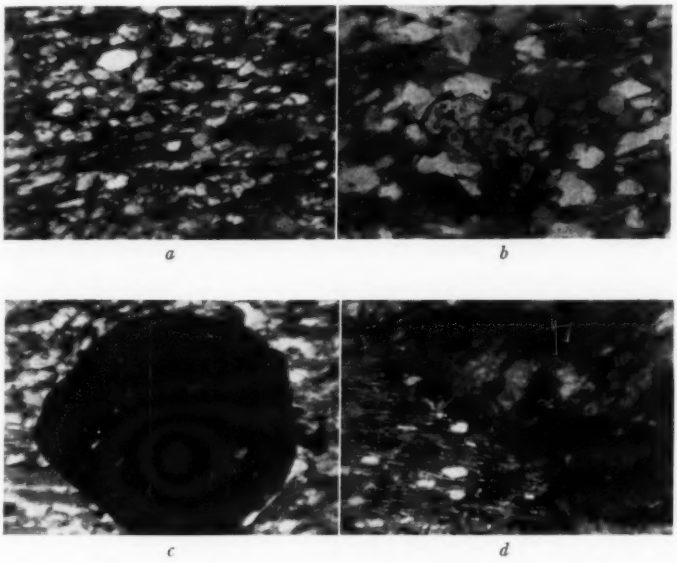
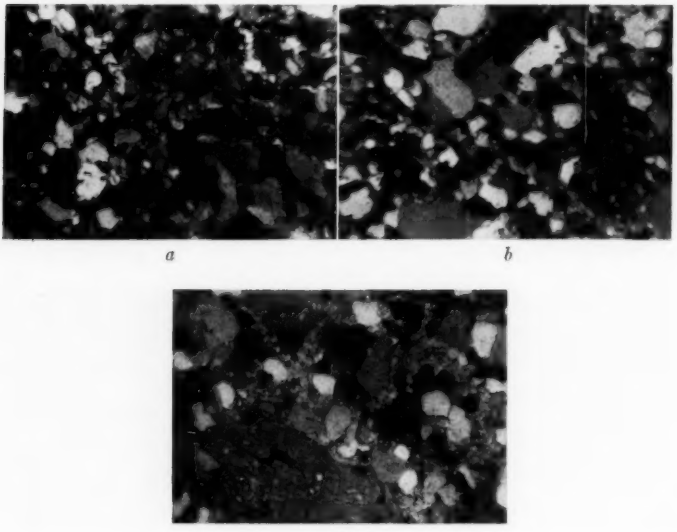


FIG. 3.—Michigamme formation converted into staurolite-garnet schist. Crossed nicols ×22. *a*.—Chiefly biotite and quartz. *b*.—Staurolite, with biotite and quartz. *c*.—Large garnet. *d*.—Interlaminated muscovite and orthoclase, with feldspar dikelet cutting across schistosity.

attraction, but this belt is lacking where the iron formation is not near the granite, although locally magnetic attraction may exist in the vicinity of basic intrusions. This development of a magnetic belt near the granite is a characteristic indication of contact metamorphism and is caused by the change of the normal, non-magnetic iron formation into a rock containing much magnetite, usually accompanied by grünerite and garnet.

Rocks of this character occur in many places near the granite and

are especially well developed in the vicinity of Beacon, Republic, and the Magnetic mine west and north of Republic. South of Beacon the Negaunee iron formation—or, perhaps, the upper, ferruginous part of the Siamo formation—has been transformed into a rock consisting of a mat of interlocking grünerite needles throughout which are scattered quartz, magnetite, epidote, and garnet, the latter mineral



a *b*

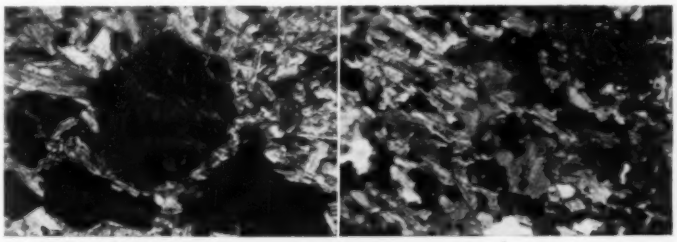
c

FIG. 4.—Gneissoid Michigamme formation. Crossed nicols ×22. *a*.—Texture similar to normal graywacke. *b*.—More gneissoid than 4a. The black, elongated mineral is chloritoid. *c*.—Shows development of poikilitic amphibole.

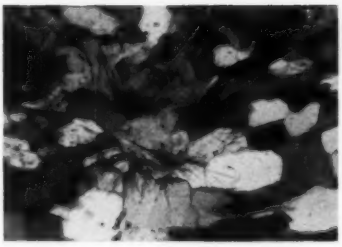
penetrated by the grünerite (Fig. 5*a*). Near Republic conditions are similar but apparently more diverse. In addition to rocks such as the one just described, some parts of the formation are much banded. Within a single thin section there may be seen a succession of laminae, some of which consist chiefly of small, interlocking quartz crystals and a peculiar amphibole showing low extinction (8° to 12°) and pleochroism in blue and green;[11] others consist of garnet, others

[11] The composition of this amphibole has not been determined, but, from its optical properties and association, it should be intermediate between riebeckite and actinolite

of grünerite, and still others of magnetite (Fig. 5*b*). Leaner phases of the formation contain much quartz as interlocking masses, magnetite, biotite, and garnet; locally there are peculiar hair-like crystals, possibly grünerite, in radiating bunches (Fig. 5*c*). In addition to these variations, some specimens show large, poikiloblastic pyroxene crystals.



a *b*



c

FIG. 5.—Metamorphosed Negaunee formation. Crossed nicols ×22. *a*.—Grünerite, garnet, and magnetite. Note grünerite needles penetrating garnet. *b*.—Banded phase. *c*.—Lean phase, chiefly quartz. The hair-like mineral may be grünerite.

Several miles west and north of Republic, near the abandoned Magnetic mine, metamorphism has been extreme. Garnet an eighth of an inch across has been developed, and may occur with magnetite in beautifully zoned crystals (Fig. 6*a*); the peculiar amphibole found near Republic is abundant, and this amphibole, together with

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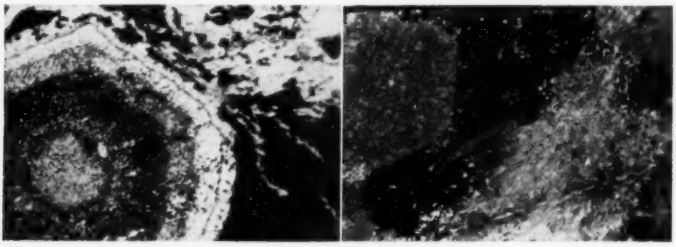
or between riebeckite and glaucophane, although oral communication from Stephen Richarz indicates that it contains no soda.

grünerite and magnetite, forms the bulk of some specimens (Fig. 6*b*). In addition to the metamorphic minerals described, the iron formation in the vicinity of the Magnetic mine is cut locally by veinlets of pyrite and chalcopyrite which have been introduced later than the amphiboles. Although not found by the writer, scheelite also has been reported twice from the iron formation in this vicinity.[12]

In the Felch Mountain district, farther south, the Vulcan iron formation has been metamorphosed in a somewhat similar manner.



a *b*

FIG. 6.—Negaunee formation near Magnetic mine. Without analyzer ×9. *a*.—Garnet, magnetite, and amphibole. Note zoned garnet and magnetite. *b*.—Chiefly amphibole, magnetite, and garnet.

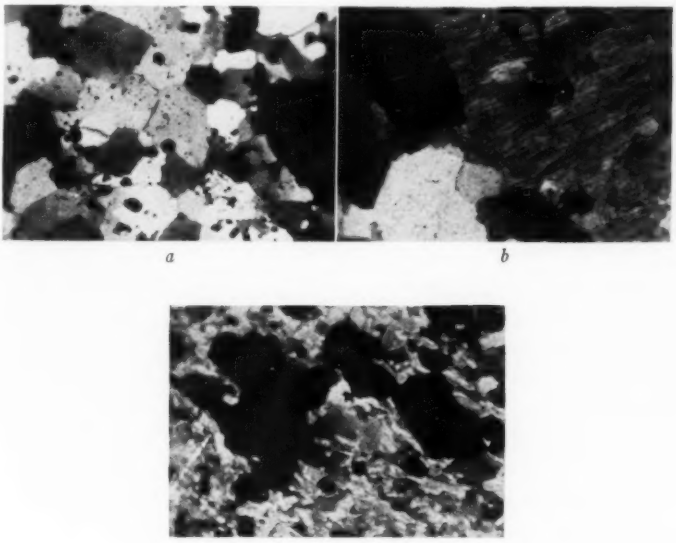
The lean, quartzose formation is composed of a closely interlocking aggregate of quartz, scattered through which are well-crystallized magnetite, specular hematite, some orthorhombic amphibole (probably feranthophyllite), chlorite, epidote, and apatite (Fig. 7*a*). Richer phases of the iron formation contain more silicates, and may be composed almost wholly of amphibole and magnetite, with some garnet, epidote, and a pyroxene resembling pigeonite (Figs. 7*b* and 7*c*). The amphiboles comprise cummingtonite and other members of the kupfferite-grünerite series of Winchell,[13] as well as the orthorhombic variety feranthophyllite. The peculiar amphibole found elsewhere is also present in the Vulcan formation.

[12] Wadsworth, "A Sketch of the Geology of the Iron, Gold, and Copper Districts of Michigan," *op. cit.*, p. 66.

[13] A. N. Winchell, "The $FeSiO_3$-$CaSiO_3$-$MgSiO_3$-$NaFeSi_2O_6$ System of Monoclinic Amphiboles," *Am. Miner.*, Vol. X (1925), pp. 335–41.

THE RANDVILLE DOLOMITE

Where exposed in quarries and outcrops near Randville and Felch, the Randville dolomite is, as a rule, a white marble containing an abundance of white and pale-green silicates. Some parts of the formation consist almost entirely of interlocking masses of these silicates. Both the amphibole and the pyroxene groups are represented



a *b*

c

FIG. 7.—Metamorphosed Vulcan formation. Crossed nicols ×22. *a*.—Chiefly quartz and magnetite. *b*.—Magnetite, quartz, and amphibole. *c*.—Chiefly amphibole and magnetite.

–the former by tremolite, actionolite(?), and feranthophyllite, the latter by pigeonite, salite, and perhaps clinoenstatite. Other silicates include phlogopite and antigorite. Locally the silicates are accompanied by pyrrhotite, pyrite, chalcopyrite, and quartz containing many inclusions of well-crystallized pyrite.

It is difficult to recognize any very definite association of minerals with respect to the granite contact, but in general it may be stated that phlogopite, quartz, pyrite, pyrrhotite, and chalcopyrite have

not been seen in outcrops some distance from the granite. Amphiboles and pyroxenes appear in the same thin section, and several representatives of each group may be present. Antigorite is particularly well developed close to the edges of granite dikes.

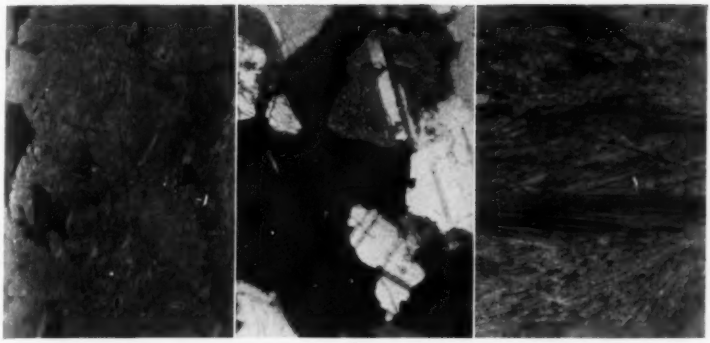
The texture of the marble varies considerably. Near the granite contact there may be seen amphibole and pyroxene crystals several inches long, phlogopite crystals $\frac{1}{2}$ inch wide, rhombs of dolomite as much as 3 inches across, and masses of pyrrhotite and pyrite. Farther away the crystals are smaller, but the texture is exceedingly variable (Fig. 8).

METAMORPHISM OF QUARTZITIC FORMATIONS

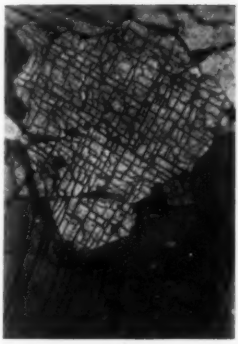
Characteristically, intrusion of the granite into quartzitic formations has resulted in the development of gneisses, but locally it has caused extensive sericitization.

In the Felch Mountain district, where the Sturgeon quartzite is close to the granite and may contain granite dikes, there occur phases showing gradation from a white or gray vitreous quartzite into a rock difficultly distinguished from granite. The change apparently proceeds by the rearrangement of the quartz into a closely interlocking mass of crystals through which, in some instances, there is scattered well-crystallized magnetite; by the development of green amphibole which may penetrate minute fractures, which may be scattered throughout the rock, or occur segregated in bunches sometimes several feet across and accompanied by pyroxene (pigeonite?) and epidote; and, near the granite contact, the development of microcline, a plagioclase near oligoclase-andesine, white mica, garnet, magnetite, epidote, and zoisite.

The development of gneiss from quartzite is well shown in the Marquette district south of Beacon and east of Lake Michigamme. South of Beacon the Ajibik quartzite nearest the iron formation is readily recognized as such, but as the granite is approached dikes appear in the quartzite, blocks of it become surrounded by granite, and the formation gradually changes into a gneissoid quartzite and then into a gneiss, followed in turn by a rock similar to a gneissoid granite and finally by the normal granite. A series of specimens representing a quarter-mile section across the steeply dipping quartzite

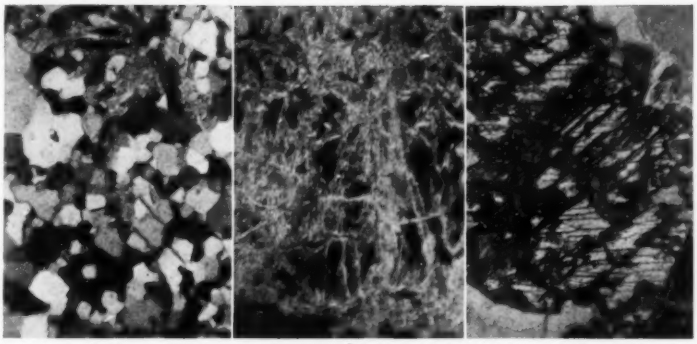


a *b* *c*



d

FIG. 8.—Metamorphosed Randville dolomite. Crossed nicols ×22. *a*.—Poikilitic pyroxene. *b*.—Pyrrhotite (black) in marble. *c*.—Chiefly tremolite. *d*.—Chiefly pyroxene. *e*.—Chiefly quartz with minute pyrite inclusions. *f*.—Serpentine (antigorite). *g*.—Serpentine developing from pyroxene.



e *f* *g*

into the gneissoid granite shows well the changes produced in composition and texture (Fig. 9). The most normal quartzite consists essentially of quartz and biotite, the latter packed around the

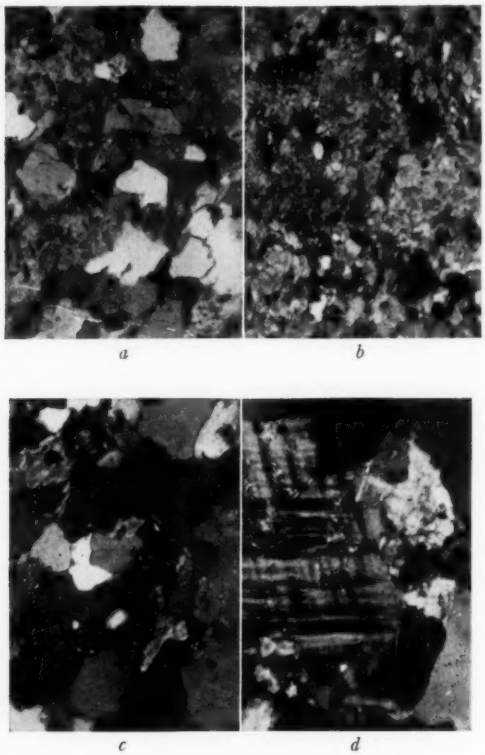


FIG. 9.—Metamorphosed Ajibik quartzite. Crossed nicols ×22. *a*.—Most normal quartzite. *b*.—Quartzite nearer the granite. Note changed texture. *c*.—More gneissoid quartzite composed chiefly of quartz and feldspar. *d*.—Contact phase. Note large feldspar.

quartz grains; small mounts of sericite and pyrrhotite are present also (Fig. 9*a*). As the granite is approached this rock gives place to one with greatly changed texture (Fig. 9*b*), composed chiefly of quartz and biotite but containing also garnet, more pyrrhotite than

previous specimens in the series, and some epidote. With closer approach to the granite the quartzite changes into a rock composed of interlocking quartz and feldspar crystals (microcline, and plagioclase near andesine-oligoclase), accompanied by biotite, garnet, pyrrhotite, and apatite (Fig. 9*c*), and finally into one composed of large crystals of microcline and microperthite, large and small quartz crystals, and sericite which has developed principally in the plagioclase feldspar (Fig. 9*d*).

In most of its essential features the metamorphism produced in the Goodrich quartzite east of Lake Michigamme is similar to that produced in the Ajibik formation south of Beacon. Thus, the quartzite grades into a gneiss and then into a gneissoid granite. The chief mineralogical difference is the presence of tourmaline and some magnetite.

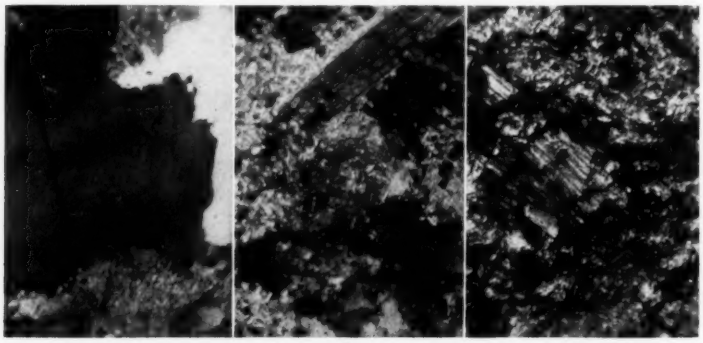
A somewhat unusual type of metamorphism is found in the Ajibik quartzite near Palmer, where sericitization has been extensive. This type of metamorphism occurs not only in the immediate vicinity of Palmer but also several miles west of there, near Lake Palmer. Because of the manner in which the granite sends cupolas into the quartzite it is difficult to obtain a series of specimens which certainly represent gradation toward the contact, as it is never known where, below the surface of an outcrop, the unobserved contact is located. Some conception, however, of the progress of contact metamorphism was obtained. The quartz grains are gradually replaced by sericite, replacement starting at the contact between grains and along fractures in the quartz, and gradually working inward until, in extreme cases, the original grains are almost completely sericitized. Although much of the mica is the fine, somewhat fibrous type known as sericite, large plates of white mica are present in some slides. Chloritoid commonly appears along with the sericite and in some instances is abundant and in large plates (Fig. 10).

Although sericitization is characteristic in this vicinity, it does not always occur. Where it is absent the quartzite has the gneissoid appearance of the Ajibik formation south of Beacon. In an early gneissic stage the quartzite is composed of an acid plagioclase, chloritoid, garnet, and apatite, in addition to quartz, sericite, and large plates of white mica; with more intense metamorphism, microcline,

microperthite, newly-crystallized quartz, biotite, and some epidote appear.

RELATION OF METAMORPHISM TO GRANITE INTRUSION

It seems apparent from the foregoing descriptions of the Huronian sediments that much of the metamorphism produced in them is directly related to the intrusion of the Republic granite. Support is given to this conclusion by an analysis of the accessory minerals of



a *b* *c*

FIG. 10.—Sericitized Ajibik quartzite. *a*.—Coarse-grained, partly sericitized quartzite. The fibrous mineral is sericite. Crossed nicols ×9. *b*.—Finer-grained and more sericitized quartzite. Note chloritoid, the large, enolgated mineral. Crossed nicols ×22. *c*.—Highly sericitized quartzite. Note chloritoid. Crossed nicols ×22.

the granite. In this analysis it was shown that, among many other minerals, pyrrhotite, pyrite, chalcopyrite, and tourmaline are accessory minerals of the granite; that in general the sulphides, especially pyrrhotite, are more abundant near the periphery of the granite than toward the interior of the mass; and that tourmaline occurs only in dikes or small outlying intrusions, indicating the escape of boron, sulphur, and perhaps also iron, toward and possibly beyond the margins of the intrusion.[14]

Some unusual features of metamorphism exist, due to the folding prior to and possibly also accompanying the intrusion of the granite. Thus there is the presence of staurolite and chloritoid, characteristic stress minerals. Nevertheless, in this instance the distribution of

[14] Lamey, *Ann. Rept. Nat. Research Council, Appendix F* (1933), pp. 3–4.

staurolite appears to be directly related to the granite intrusion, and staurolite is known to originate under such conditions.[15] Again, although chloritoid has a great stability range and may persist in rocks in which it was developed by regional metamorphism, even after the intrusion of granite,[16] it has been shown to form during contact metamorphism.[17] Another unusual phase of contact metamorphism is the sericitization of an impure quartzite. It is well known that extensive sericitization may result around an intrusive mass,[18] but instances of the sericitization of a quartzite are rare.

[15] Van Hise, "A Treatise on Metamorphism," *U.S. Geol. Surv. Mono. 47* (1904), p. 327; G. W. Tyrrell, *The Principles of Petrology* (New York: Dutton, 1926), p. 290; Waldemar Lindgren, *Mineral Deposits* (3d ed.; New York: McGraw-Hill, 1928), p. 788.

[16] Alfred Harker, *Metamorphism* (London: Methuen & Co., 1932), p. 323.

[17] C. E. Tilley, "Petrographical Notes on Some Chloritoid Rocks," *Geol. Mag.*, Vol. LXII (1925), pp. 309–19.

[18] Lindgren, *op. cit.*, pp. 197, 602–14.

DRAINAGE HISTORY OF SOUTHEASTERN OHIO AND ADJACENT WEST VIRGINIA

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ABSTRACT

Topographic maps strongly support Tight's restoration of former main drainage lines in southeastern Ohio and adjacent West Virginia, but suggest numerous changes of detail, and the possibility of a more complex history than Tight recognized. No definite confirmation of Tight's theory of the manner of drainage diversions has been found. Structural control is abundantly indicated in the region, and may have been a factor in some of the drainage changes. Some evidence suggests that the former drainage may have been originally consequent on Appalachian uplift, either in late Paleozoic or more recent time. Indirect evidence, of uncertain validity, suggests that at least part of the present drainage may have been superposed from a sedimentary cover more continuous than the valley silts, which Tight considered the cause of the drainage changes.

INTRODUCTION

This paper presents the results of a study of the map evidence bearing on Professor W. G. Tight's interpretation of the drainage history of southeastern Ohio and adjacent West Virginia. Thirty years have passed since Tight presented his final conclusions,[1] which since then have been generally accepted as part of the history of Pleistocene glacial effects. There has been no later contribution suggesting fundamental changes in Tight's interpretation; yet there were several reasons for undertaking a restudy of the problem.

First, the very fact that topographic maps are now available for the area challenged consideration, especially since Tight commented on the difficulties he encountered because of lack of adequate maps. Second, Tight presented some of his results as tentative and worthy of further study. Third, the possibility of an alternative explanation of the cause of the drainage changes in the area has been suggested by Leverett's discussion[2] of possible Pleistocene submergence in northern Kentucky, and Johnson's presentation[3] of the evidence

[1] William G. Tight, "Drainage Modifications in Southeastern Ohio and Adjacent West Virginia and Kentucky," *U.S. Geol. Surv. Prof. Paper 13* (1903).

[2] Frank Leverett, "The Pleistocene of Northern Kentucky," *Ky. Geol. Surv.* (6), Vol. XXXI (1929), pp. 1–80.

[3] Douglas Johnson, *Stream Sculpture on the Atlantic Slope* (New York: Columbia Univ. Press, 1931).

favoring regional superposition of Atlantic slope drainage from a former extensive sedimentary cover.

GENERAL DESCRIPTION OF THE REGION

The area studied in detail includes some 12,000 square miles (Fig. 1). This is a maturely dissected, moderately fine-textured part of the Kanawha section of the Appalachian Plateau. The altitude

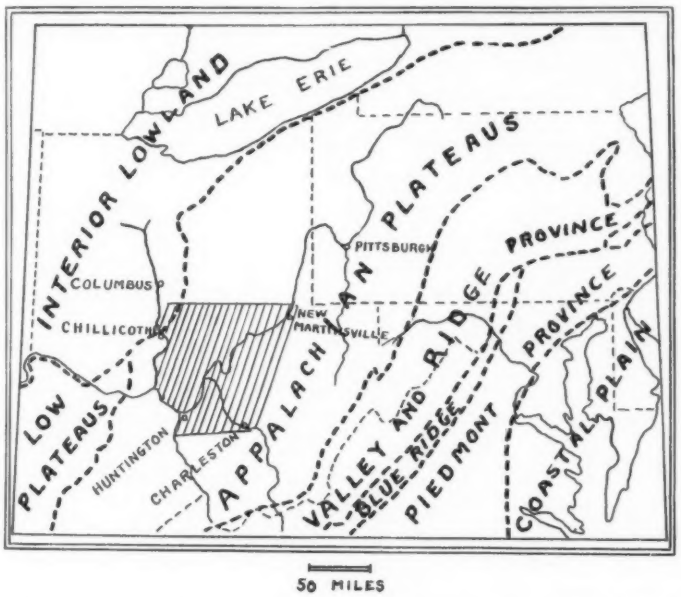

FIG. 1.—Location of the area studied, shown by oblique ruling, in relation to physiographic provinces.

varies from 500 to 1,500 feet, with the local relief ranging from 300 to nearly 1,000 feet. But for a small section at the northwest, it lies outside the boundary of Pleistocene glaciation.

The regional structure is synclinal, the area being part of the Pittsburgh-Huntington coal basin, the axis of which trends northeast-southwest across the eastern part of the area. Northwest of this axis the beds rise gently toward the Cincinnati arch; southeast of it they

rise gently toward the Allegheny front. Dips average perhaps 25 feet per mile. Steeper dips occur locally, and there are also numerous minor folds, but these variations from regional structure are not reflected in topography.

The entire area is underlain by Carboniferous sedimentary rocks, ranging in age from Lower Mississippian to Lower Permian. The

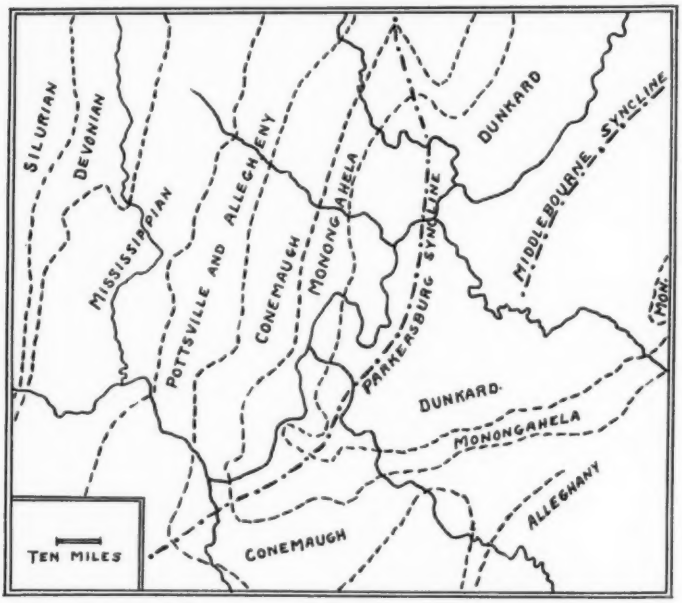

FIG. 2.—Areal geologic map, generalized from geologic maps of Ohio and West Virginia.

Mississippian includes the Waverly and Maxville sandstones, shales, and limestones, overlain by the Pennsylvanian Pottsville series, in which heavy conglomeratic sandstones are prominent. Above the Pottsville are the Allegheny, Conemaugh, and Monongahela series, all Pennsylvanian, and comprising alternating beds of shale, sandstone, coal, and occasionally thin limestones. The Dunkard series of basal Permian age is chiefly red shale and irregular yellow sandstone, with occasional calcareous and carbonaceous beds (Fig. 2).

Considerable deposits of unconsolidated, laminated silts, nearly 100 feet thick in places, are found chiefly in the bottoms of old valleys which now have no through-going drainage, and in the lower parts of many of the smaller valleys. In the present main valleys, except parts of the Kanawha, these silts largely have been removed wherever once present; and the valleys are now filled to considerable depths with sands and gravels, which have been terraced by the present streams. In all of the valleys which have carried glacial waters, these coarse, fluvial deposits are very prominent, and are there composed chiefly of outwash material.

METHODS OF STUDY

Three special methods have been used to supplement such information as could be gathered from simple inspection of the topographic maps.

Detailed tracing has been used to determine the pattern of former drainage. It was found possible to trace, with considerable detail and assurance, the contact between steep valley sides and gently sloping valley bottoms.

Topographic maps have been colored, using a sequence of colors for successive 100-foot contour intervals, to outline the valleys, emphasize the ridge and spur patterns, and trace the more prominent divides.

Projected profiles, of the Barrell type, were used to restore the supposed former erosion surface now represented by the accordant summits throughout the area. A grid of east-west and north-south profiles was constructed, each profile representing a strip 2 miles wide, the strips being taken at 5′ intervals of latitude and longitude with the 5′ lines on the topographic maps serving as base lines for the profiles.

SUMMARY OF TIGHT'S CONCLUSIONS

The relation of present to former drainage, as restored by Tight, has been mapped (Fig. 3). The lower course of the Albany River has been revised according to map evidence, a revision which is of the nature of a simplification and has been previously described by Stout.[4]

[4] Wilber Stout, "Geology of Vinton County," *Ohio Geol. Surv.* (4), *Bull. 31* (1927).

The main axial stream of the former drainage was the Teays, with the Marietta River as its chief tributary. The Teays, carrying the headwater drainage of the present Kanawha, diverged from the Kanawha Valley at St. Albans, followed the now abandoned Teays Valley to Huntington, approximately followed the present Ohio course to Wheelersburg, Ohio, turned north through the California

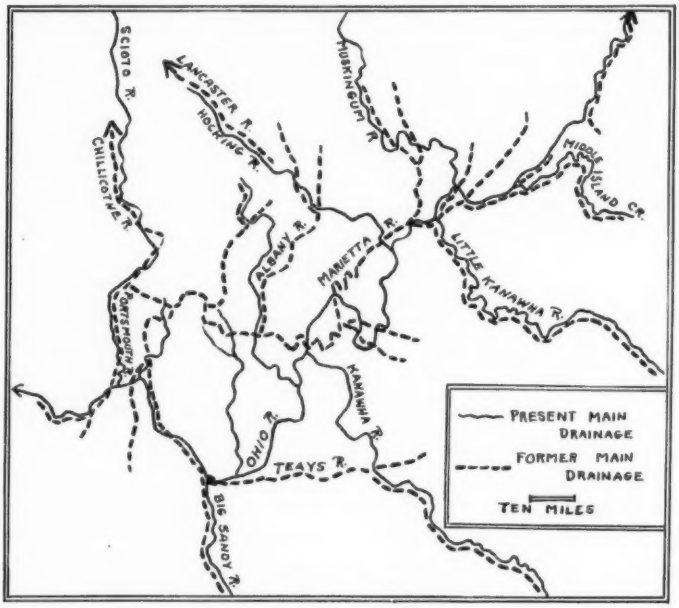

FIG. 3.—Present main drainage, shown by solid lines, and former drainage, shown by broken lines.

Valley to Glade, thence northwest to Waverly, and approximately reversed the present Scioto course to flow past Chillicothe to the northwest, where its course is now lost beneath the heavy glacial deposits. The Marietta River, heading in the Little Muskingum and probably Middle Island Creek which enters the Ohio at St. Marys, West Virginia, roughly paralleled the present Ohio to Gallipolis, where it turned west to Oak Hill, then north to Jackson, and finally southwest to join the Teays near Glade. The chief tributaries of the

Marietta were the Little Kanawha from the southeast and the Albany from the north, the latter carrying most of the present Hocking drainage.

Tight's interpretation of the sequence of events, by which the present drainage developed from the former, may be summarized as follows:

1. Peneplanation followed by uplift and drainage entrenchment.
2. Development of mature topography with breaching of many divides by headward stream erosion, producing numerous low cols.
3. A slackwater period of silting—believed due to blocking of the northwestward drainage by an early glacial advance.
4. Diversion of streams across many cols, due to more rapid aggradation of the main drainage lines.
5. Incision of the new drainage as the ponded waters were drained—by whatever circumstances this was effected.

CORROBORATION OF TIGHT'S RESTORATION OF FORMER DRAINAGE

The results of this study are all conformable with Tight's general conclusions, and in some respects offer strong confirmation, concerning the direction, nature, and main lines of former drainage. Seven lines of evidence were considered, and all were found to support Tight's statements.

1. The first problem was to trace the former drainage lines, to be sure that the maps confirm Tight's observations concerning the continuity of the old valleys. The results were confirmatory, with some exceptions noted on the following pages—exceptions which are all in regard to details and do not raise serious objections to Tight's general conclusions.

2. The second problem was to check Tight's altitude determinations, upon which he placed considerable reliance as evidence of the direction of flow of former drainage. The maps offer no way of determining directly the altitude of old valley floors measured by Tight, since those valley floors are now buried beneath silts and gravels, and determinable only from excavations and well records. It is possible, however, to check the altitude of many of Tight's control points, which were chiefly from railroad surveys.

The results are quite confirmatory, within the limits of accuracy of the 20-foot contour interval of the maps. Of twenty-nine points which could be checked with assurance, Tight's figures for twenty-three are within the interval shown by the contours. For one station, Coolville, Tight's figure is 627 feet where the map shows a possible range of 580–620 feet, a discrepancy of slight importance. The figures given for five stations on the Cincinnati, Hamilton, and Dayton Railway, the only stations on this line that could be checked, are consistently 40–60 feet higher than the altitude shown on the maps. Almost certainly such a discrepancy indicates an error in the railway survey, but this did not lead Tight into any false conclusions, perhaps partly because he knew and discounted the weakness of some of his data, and also because these figures did not come into any important calculations.

3. Colored contour maps were particularly helpful in showing the pattern of ridges and spurs. These in turn serve to outline the valleys, and thus show a typically dendritic pattern for the former drainage. They show tributaries entering the main valleys either at right angles or pointed downstream; whereas, exceptions to this rule are rather numerous in the case of the present drainage. The former drainage is considered much better adjusted to topography than is the present drainage. This cannot be illustrated, since it is not practicable to reproduce the colored maps.

4. The relatively higher and more continuous ridges, which have been traced from the colored maps and also recognized on the projected profiles, are believed to represent former main divides. They are clearly independent of structure, with local exceptions, and have the sinuous form, with numerous branching spurs, characteristic of major divides in the Appalachian plateaus. The writer finds these divides where Tight located them, with minor variations such as are expectable with the more detailed and accurate maps now available. They are, of course, nowhere crossed by the restored drainage lines, though diversion is thought to have occurred wherever they are crossed by the present streams.

5. Barbed tributaries occur above the Winfield and Crown City, and the New Martinsville cols, where it is believed the Kanawha and Ohio, respectively, cross former divides (Fig. 4). The writer con-

siders these barbed tributaries strong confirmatory evidence of drainage reversal, because of the contrast of their pattern and that of tributaries on the opposite side of the supposed col and also because they are clearly not due to structural control. It is noted that barbed tributaries are practically absent in the region, with the exception of places where there are other reasons for suspecting drainage reversal.

The structure is similar at the Winfield and Crown City cols, with the exception of the direction of dip, which is reversed, for a synclinal axis passes between the two cols. At Winfield the barbs point up dip; whereas at Crown City they point down dip, indicating that the barbs are not due to structure. There seems to have been not simple reversal at Winfield, but considerable readjustment, which is reflected in the irregularities of the stream pattern. At Crown City the barbs are not conspicuous by themselves, but contrast strongly with the situation south, or downstream, from the former col where the tributaries consistently point downstream.

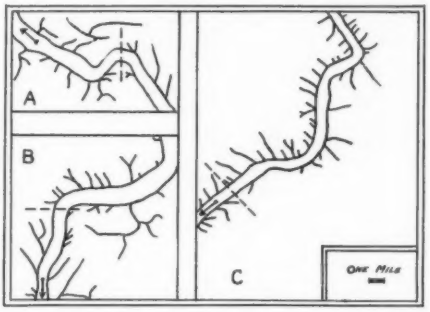

FIG. 4.—Barbed tributaries at the Winfield, Crown City, and New Martinsville cols. Main valleys are shown as of the width of floodplains and alluvial terraces, tributary valleys shown diagrammatically. Position of former divides shown by dashed line.

The situation at New Martinsville does not seem as convincing as it would if it were practicable to figure a larger area in sufficient detail. Downstream from the former col tributaries are quite uniformly pointed downstream, and upstream they are much less uniform in trend and many are distinctly barbed. The evidence here includes the absence of barbs downstream, since structural control cannot be the cause, for the dip is consistently to the east on both sides of the former col.

The location of former cols at Bluerock on the Muskingum and at Lick Run on the Hocking, a few miles below Haydenville, is also sup-

ported by the crossing here of supposed former divides in relatively deep, steep-sided valleys, with barbed tributaries occurring upstream, and the general pattern of ridges showing a change in trend, pointing distinctly downstream below the col and somewhat less certainly upstream above the col.

6. From inspection of maps the abandoned Teays Valley, between St. Albans and Huntington, appeared surprisingly rectilinear. This was particularly noticeable in contrast with the pattern of the Kanawha above St. Albans, which seemed quite accordant with its pattern below that point. This seemed anomalous, since the Upper Kanawha–Teays was supposed to have been the stream incised from a peneplane, and the lower segment of the Kanawha represented accidental post-entrenchment extension of the upper Kanawha.

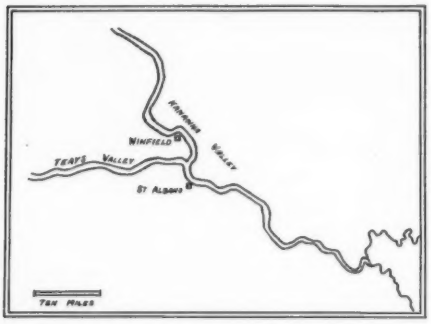

FIG. 5.—Pattern of the Teays and Kanawha valleys, as shown by detailed tracing.

Detailed tracing of these valleys produced illuminating results (Fig. 5). The apparent rectilinear nature of the Teays Valley proves to have been an illusion. The pattern of curvature of the Teays–Upper Kanawha is actually better accordant than the Lower Kanawha–Upper Kanawha appeared to be. The abandoned section of the Teays Valley shows a gradational change from the rather angular bends of the Upper Kanawha to the gently sinuous course which the Teays must have had to follow along the line of the Ohio from Huntington to Wheelersburg.

7. Projected profiles served as a basis for restoration of the former surface represented by the accordant summit elevations of the area (Fig. 6). Whether the restored surface represents a former peneplane, or even parts of two or more peneplanes, is not yet certain; but the significant fact, for the present purpose, is that, with two exceptions, it clearly shows a general slope toward the former main drainage lines.

The cuesta-like upland extending in a north-south direction near the Scioto, in the western part of the area, is undoubtedly a reflection of structural control. The western scarp of this cuesta is developed chiefly on resistant Mississippian sandstones, and the eastern part is held up by the heavy conglomeratic sandstone of the Pottsville. It is quite natural that these rocks should stand higher than the surface developed on weaker Pennsylvanian and Permian strata farther

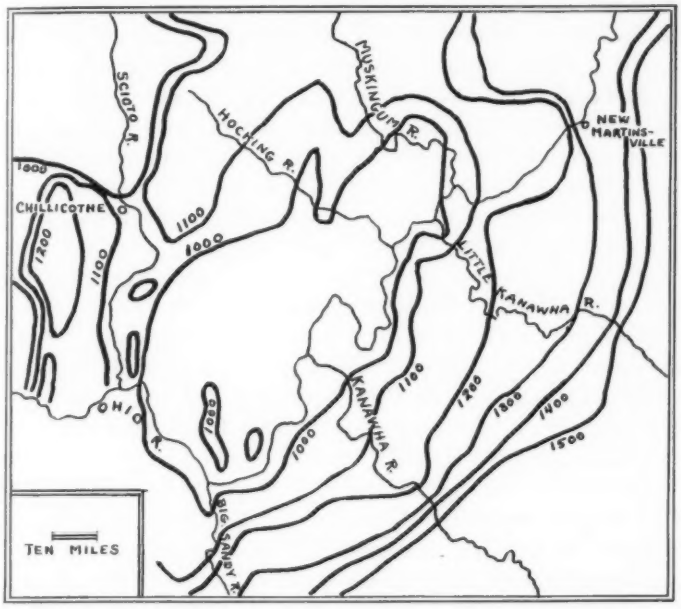

FIG. 6.—Contour map, drawn from projected profiles, of restored surface represented by summit elevations. Contour interval is 100 feet.

east. The existence of this upland standing partially athwart the course of former drainage is therefore not anomalous.

A condition more difficult of explanation is the wider development of the lowest part of the former surface (below 1,000 feet) in the Marietta drainage area than on similar rocks in the Teays drainage, since the latter was the largest and master stream of the region. The profiles show a long slope from the south toward the Teays Valley, but a comparatively short and slight rise northward to the Teays-

Marietta divide. Indeed, on some of the profiles it requires careful examination to see that there is not a single continuous slope to the north toward the Marietta basin, passing over the Teays Valley without break in slope, so faint is the relief of parts of the Teays-Marietta divide above the general restored surface. Two partial explanations are offered, but this situation still remains a problem.

The abandoned section of the Teays Valley in West Virginia is relatively very close to the divide between it and the Marietta drainage. This section of the Teays is almost parallel to the strike of the underlying rocks, and the dip is to the north. Near where the Teays crosses the axis of the Parkersburg syncline a few miles east of Huntington, so that the dip is reversed, the valley begins to diverge from the former main divide north of it. Also, farther to the southeast where the Kanawha, or former Teays, flows nearly normal to the strike, it has long tributaries from the north and the limiting divide is far away. These conditions strongly suggest structural control. Whether the Teays slid down dip to the north, or the Marietta tributaries were so favored that they pushed the divide southward, by headward erosion, almost to the edge of the immediate valley of the Teays itself, or whether both processes operated, it seems probable that the Teays and its limiting divide gradually may have approached each other. This may account for the asymmetry of the Teays Valley and the resulting appearance of a nearly continuous slope across the Teays toward the Marietta, and is especially interesting as a possible contributary cause to the diversion of the Teays northward across the Winfield col.

The preceding suggestion fails to explain the fact that the restored surface has a lower altitude, or at least a wider development at the lower levels, in the Marietta than in the Teays basin. The contours which extend almost directly across the Teays drainage, on the restored surface, swing back to the east in a wide curve around the Marietta drainage basin. A structural advantage enjoyed by some Marietta tributaries can hardly account for this, since most of the Marietta drainage had no such advantage. The only logical explanation which can be offered now is that of warping since the development of this old surface, which may have been a peneplane. There is, however, no other known evidence to support such a theory of warping.

EVIDENCE OF STRUCTURAL CONTROL

Structural control, operating through the usual medium of relative resistance of different strata, seems to have been a major factor in the erosional history of the region.

The influence of resistant sandstone members is apparent, practically throughout the entire region, in rock benches and cliffs on the hillsides. These are seldom recognizable on the maps, but in the field they are one of the most conspicuous features of the landscape. They are especially well shown along the Ohio River between Marietta and Parkersburg, where there are three sandstone cliff-makers showing frequent outcrops. Above each cliff is a bench, behind which a steeper, soil-covered slope rises to the base of the next nearly vertical cliff.

The prominent upland across the western part of the area, which has already been described as essentially a dissected cuesta, has a strong scarp facing west. This is one of the most significant and prominent topographic and physiographic features of the region, and an indisputable evidence of structural control.

Attention has been called already to the strong suggestion of down-dip migration of the Teays Valley in West Virginia, east of the axis of the Parkersburg syncline. It may be that similar migration of the Marietta River also occurred, but southward, west of the synclinal axis, where the dip has a southerly rather than northerly component. The Marietta from its headwaters, which were the Little Kanawha, Little Muskingum, and probably Middle Island Creek, to Jackson where it entered the narrow, constricted lower part of its valley through the Waverly-Pottsville cuesta, followed a roundabout course with a wide arc to the south. If the original stream flowed more directly west from the mouth of the Little Kanawha, which is close to the Parkersburg axis, to Jackson, the lower part of the stream may have been held as in a vise by the heavy sandstones of the cuesta, while the middle portion migrated south to the course which it had immediately prior to silting, via Point Pleasant and Oak Hill.

Many asymmetrical valleys are seen in the northern part of the area, which strongly suggest structural control. Perhaps the most conspicuous is the section of the old Albany Valley, in the southern part of the Athens quadrangle, where it trends north-south and the dip is about east-southeast. Tributaries from the east are all less than

3 miles long, and those from the west average about 8 miles. The divide to the east has many summits reaching 1,000 feet within 3 miles of the valley, whereas to the west there are few summits reaching this altitude within 10 miles of the main valley. The spurs extending toward the valley from the eastern divide are notably short, and maintain an altitude of 900 feet for only about 2 miles; those extending east from the western divide maintain that elevation for at least 6 miles, on the average. The asymmetry is striking and well adjusted to structure.

A similar situation exists, although not quite so prominently, in the adjacent valleys to east and west. These are the old valleys now drained by Raccoon Creek in the Zaleski quadrangle, and by the Hocking and its tributary, Federal Creek, in the Chesterhill quadrangle. In each case the former main valley is distinctly nearer the eastern than the western divide, as in the case of the Albany Valley.

The Zaleski quadrangle offers particularly prominent examples of asymmetric northeast-southwest valleys, with long down-dip tributaries from the northwest and short up-dip tributaries from the southeast, shown by four old valleys, one passing through Zaleski, one along Twomile Run and part of the present Raccoon toward Elk Fork, another along the present East Branch through Plymouth, and the fourth following the valleys of Honey Fork and Brushy Fork through Orland and Creola. In contrast with these are the northwest-southeast valleys of the West Branch and several tributaries of Brushy Fork, which extend nearly directly down dip and show no asymmetry.

A similar structural control, but indicated by the alinement of the trend of ridges, is well shown in the McConnelsville quadrangle. With two exceptions, all of the ridges here trend northwest-southeast, roughly parallel with the dip. One of the exceptions trends a little east of north through Ringgold, the other north of east through Triadelphia; both of these are parts of former major divides, and may be compared to backbones from which the other ridges extend as ribs. The Triadelphia ridge almost certainly was once part of a major divide north of the Marietta drainage, and the Ringgold ridge was part of a branch from this main divide, the general trend of which was southeast. These exceptions are therefore not incompati-

ble with the other evidences of structural control; obviously, the divides between streams flowing west must also trend west, regardless of the structure.

It is noted that evidence of subsequent adjustment to structure is not found universally throughout the region. The majority of the valleys show a dendritic pattern, with only the irregular variations from approximate symmetry such as are expectable from accidental factors. Most of the ridges are sinuous and not apparently controlled by structure. On the other hand, not a single case has been found of valleys or ridges showing asymmetry or alinement not in accord with the structure. In a region of nearly horizontal rocks, with the resistant members rather thin and irregular, the significant fact seems to be, not the failure of structural control to be everywhere apparent, but rather the considerable extent to which it is recognizable.

It is also noted that Campbell[5] has assigned asymmetry of drainage basins, immediately east of the area here considered and elsewhere in the southern Appalachians, to surface adjustments of drainage following relatively recent tilting, independent of structural control in the sense here used. Where such tilting sufficed to produce a structural dip in the direction of tilting, there would seem to be no way to determine which effect had operated, with the exception of the rare case in which the tilting is demonstrably more recent than any bedrock removal sufficient to bring into play the effects of relative resistance of different strata. If tilting, however, had produced asymmetry of drainage basins to the extent and on the scale noted in this area, by the essentially surficial process suggested by Campbell, it seems that in at least some cases the tilt would cause surface readjustments without being sufficient to establish a structural dip in the direction of down-tilting. Since in no case this situation of asymmetry out of accord with structure has been found, it seems more probable that adjustment has occurred during bedrock erosion by the processes usually associated with the development of structural control than by a surficial adjustment of drainage basins as suggested by Campbell.

[5] M. R. Campbell, "Drainage Modifications and Their Interpretation," *Jour. Geol.*, Vol. IV (1896), pp. 567–81, 657–78.

THE OHIO-TEAYS-KANAWHA TRIANGLE

The most puzzling physiographic problem in the region is that of the origin of the triangle formed by the Ohio, Teays, and Kanawha valleys in West Virginia. There seems no more logical explanation available than that offered by Tight; yet it remains difficult to accept fully, without more direct proof, his explanation of changes of such magnitude. The very special combination of circumstances required for diversion of the master-stream of the area first across the Winfield col into the basin of its tributary, and then back across the Crown City col into the master Teays Valley again, would not be impossible; yet it would be very unusual, especially since the Marietta drainage presumably would have been ponded just as soon as the Teays. This study has failed to produce any evidence bearing directly on the question. The most promising method of further investigation would seem to be the detailed study of the unconsolidated deposits in these valleys.

REVISED COURSE OF THE ALBANY RIVER

Stout[6] has described a revision of the course of the Albany River, as noted previously in this paper. The writer finds this revision well supported by the map evidence. There is clearly an open valley by which the Albany waters presumably passed southward from Wilkesville directly to the Marietta, instead of taking the roundabout course figured by Tight, via Dundas and Wellston. Moreover, this course via Dundas crosses what appears to be one of the former main divides, now represented by relatively high ridge crests, although breached in places. The revision is thus a simplification, tending to strengthen Tight's general theory.

CONDITIONS IN THE GLENWOOD AND WINFIELD QUADRANGLES

In the Glenwood and Winfield quadrangles, according to Tight, the Ohio and Kanawha now occupy the courses of former northward-flowing tributaries of the Marietta. The maps show two possible stream courses, at elevations comparable to those of nearby abandoned valleys, extending east-west between the Ohio and Kanawha. These were not mentioned by Tight, and the writer does not know

[6] *Op. cit.*

whether they contain silt deposits. One of them is now occupied, in parts, by the two Sixteenmile creeks, tributary respectively to the Ohio and Kanawha. The other is drained chiefly by Ohio Eighteenmile Creek and Kanawha Five-and Twentymile Creek, with a small section between these drained by Guyan Creek. The latter valley is only 2 miles, at its eastern end, from the mouth of Hurricane Creek, which drains part of the abandoned Teays Valley before cutting through the former Teays-Marietta divide to enter the Kanawha below the Winfield col. The presence of these old valleys in such a position suggests that the overflow waters crossing the Winfield col would have two available channels for reaching what is now the Ohio without the long circuit to Point Pleasant, which Tight's theory calls for. If these valleys were in existence at the time of diversion of the Teays, then the course of the present Kanawha in the Winfield quadrangle is much more difficult to account for than Tight supposed, for it extends almost directly across these former valleys. Such wholesale disregard of former valleys by the new drainage suggests superposition from a thicker and more continuous cover than the valley silts are supposed to have been.

CONDITIONS BETWEEN MARIETTA AND POINT PLEASANT

At Little Hocking, Parkersburg quadrangle, the Ohio turns abruptly southward, leaving the old Marietta Valley and crossing two former divides, at New England and Murraysville, to enter the Sandy Creek Valley. It then swings to the northwest, crossing four former divides as well as the old Marietta Valley before turning south again, along a former minor valley, to Point Pleasant. Such wholesale shift of a large stream, from a well-defined valley to a course cutting directly across numerous spurs and tributary valleys, seems, as does the situation in the Winfield quadrangle, more suggestive of general drainage superposition than mere diversion within the valley system.

In the Marietta and Parkersburg quadrangles the maps show two high-level valleys which Tight did not recognize. One extends through Valley Mills in the southwestern part of the Marietta quadrangle, with both ends opening into the Ohio Valley. The other extends from the Little Kanawha, just south of Parkersburg, via Lu-

beck to the Ohio at Meldahl. These may be parts of the old Marietta Valley, from which the Ohio has been diverted in the same way, whatever that may have been, as south of Little Hocking, or they may be remnants of old valleys confluent with the Marietta, which happened to extend for some distance close and roughly parallel to the Marietta, perhaps as Yazoo streams. In the latter case, the Valley Mills channel presumably carried the drainage of the present Ohio from the Little Muskingum to the divide at New Martinsville, but it is uncertain whether the Little Muskingum also should be considered part of this drainage or left as the main head of the Marietta, which otherwise would dwindle to relative insignificance beside this Valley Mills river. In a similar interpretation, the Lubeck channel would represent part of the old Little Kanawha, but it is not clear whether the Valley Mills stream should be considered part of this stream or whether it probably entered the Marietta at Parkersburg. The true significance of these features is not clear, but they certainly suggest a more complex history than Tight described.

POSSIBLE CONSEQUENT ORIGIN OF THE TEAYS RIVER

Throughout West Virginia and eastern Kentucky the drainage of the Appalachian Plateau is so consistently toward the northwest as to suggest either common origin or development under similar control. The logical explanation, provided there has been no later sedimentary cover over the area, would be that the drainage has existed thus since the Paleozoic, and represents the drainage consequent upon original Appalachian uplift. In the case of the Teays, the former master-stream of the region here considered, there is some indirect evidence favoring such an interpretation.

The earliest Teays would presumably be extended in the direction of retreat of the Paleozoic sea, as the land continued to emerge. This direction would be northwest at first, normal to the axis of uplift; however, the last remnant of the sea may have withdrawn either northwest or southwest, around the Cincinnati arch. If the former was the case, the entire course of the Teays was of consequent origin, and is thus accounted for. It is true that the course is up dip beyond Huntington, but this may not be a difficulty. Huntington is near the structural bottom of the southern part of the Pittsburgh-Hunting-

ton coal basin; so that all directions are up dip; and hence any consequent stream through Huntington must have originated under conditions unlike the present. That conditions permitting such origin of the Teays may have existed at the close of the Paleozoic is not an unreasonable expectation, for in the first place the present structure may not then have existed, and in the second place, even with the present southeasterly dip throughout most of Ohio, the topmost beds may have had a surface sloping toward the northwest.

If the final retreat of the Paleozoic sea was southwestward, then the headwater Teays drainage must have become tributary to a longitudinal master consequent flowing in that direction. In this case the preglacial Teays must have been formed by the piracy of an obsequent stream working headward to the southeast and cutting the master-stream near where it was joined by the upper Teays. There seem to be strong objections to the probability of such development.

First, there is now no recognizable remnant of such a southwest-flowing master-stream, with the possible exception of part of the former Marietta. It seems unlikely that a master-stream should be so completely dismembered by piracy as not to be recognizable in segments of the present streams.

Second, if such a master-stream were cut by an obsequent working southeast, it would hardly be by an obsequent having the long course of the California Valley through the resistant sandstones of the Mississippian and Pottsville. The former Marietta had a much shorter course across these rocks. and a stream working headward along that course also would have the advantage of attacking the master-stream nearer its head; so that if capture had occurred, it would probably have caused diversion of the Upper Teays into the Marietta drainage, rather than the course which it did have prior to silting. If, on the other hand, the California Valley was opened first and the old master-stream diverted into it, then the Marietta hardly could have worked back fast enough to behead at some later time the stream into which it was itself flowing. Thus it seems unlikely that piracy by obsequent drainage would have resulted in the arrangement of streams which existed in the period just prior to silting.

Finally, there is a structural feature which offers a possible clue.

The axes of the Cincinnati arch and the Pittsburgh-Huntington basin diverge northward, but the former plunges to the north and the axis of the latter rises to the northeast. The result is that the Carboniferous escarpment swings in a wide arc from a northerly strike in southern Ohio to an easterly strike in northeastern Ohio, with a structural sag where the strike changes. The Teays crossed the escarpment within this sag.

This structural condition would not give advantage to an obsequent stream working headward, so that if the Teays were captured by such an obsequent, it would be only accidentally that the course lay within the sag. On the other hand, if the Teays were entirely of consequent origin, extended to the northwest as the Paleozoic sea retreated, it would cross the escarpment through this sag. This combination of circumstances suggests that the Teays may have maintained its course essentially unchanged during the long interval from the Paleozoic to the Pleistocene.

POSSIBILITY OF DRAINAGE SUPERPOSITION FROM A FORMER CONTINUOUS SEDIMENTARY COVER

One reason for undertaking the present study, as previously noted, was the interest aroused by Leverett's[7] discussion of possible Pleistocene marine submergence in northern Kentucky. If submergence, either marine or lacustrine, has occurred in southeastern Ohio, it may have caused a more widespread sedimentary blanketing than Tight recognized, so that essentially new, consequent drainage may have developed as the surface was again exposed. (Of course such submergence may also have been associated with the slack-water conditions without involving any changes in Tight's theory.)

This possibility has been particularly interesting in view of Johnson's recent suggestion, also previously noted, of a former much greater inland extension of the Atlantic coastal plain sediments, with superposition therefrom of the present drainage of the Piedmont and folded Appalachians. If such a sedimentary cover formerly existed over such a large area on the Atlantic slope, where now there is no known remnant, it is at least conceivable that the western side of the Appalachian plateaus may have had a similar history.

[7] *Op. cit.*

The most satisfactory evidence bearing on such a problem must be field evidence. Remnants of a former sedimentary cover would be the most, and perhaps the only, satisfactory evidence of the existence of such a cover. In the absence of such proof, the strongest suggestion of regional drainage superposition appears in the conditions within the old Marietta basin, where Tight's theory may prove inadequate to account for all of the changes, which in some respects seem more easily explained as due to superposition of new drainage upon an older system. The fact that this situation is apparent only in the Marietta basin may be due to tilting, resulting in a relatively deeper submergence and consequently thicker blanketing of the Marietta basin than of the Teays drainage to the south.

In summary, the maps suggest the possibility of a former more extensive sedimentary cover than Tight recognized, but not necessarily throughout the entire region, though the negative field evidence is still strongly against such an interpretation.

SUMMARY OF CONCLUSIONS

A study of topographic maps, which were not available when Tight made his studies, has revealed seven lines of evidence supporting his restoration of former drainage in southeastern Ohio and adjacent West Virginia, as follows:

1. Tracing of drainage lines, as restored by Tight, shows that such drainage would be possible.

2. Topographic maps support Tight's altitude determinations, and thus help verify the direction of former drainage.

3. Ridges and spurs have patterns accordant with the restored drainage.

4. Contour maps and projected profiles support Tight's tracing of former main divides.

5. The presence of barbed tributaries supports the interpretation of drainage reversal at Winfield on the Kanawha, and at Crown City and New Martinsville on the Ohio.

6. Detailed tracing shows that the abandoned Teays Valley is remarkably accordant with the Kanawha Valley above St. Albans, thus supporting the theory that they are parts of a former continuous valley.

7. Projected profiles show that the surface represented by the accordant summit elevations of the region, perhaps a former peneplane, has a distinct slope toward the main lines of restored drainage.

No map evidence has been found which is incompatible with such a restoration. Many minor revisions of details are suggested by the map study, but these do not alter the general plan of former drainage as restored by Tight.

The map study has failed to yield either confirmation or contradiction of Tight's theory of the cause and manner of drainage changes. It is concluded that this problem deserves further field study.

Structural control has been observed to be reflected in several kinds of topographic features and is widely recognizable throughout the region. It seems certain that structural control has been a major factor in the physiographic development of the region.

Some evidence suggests that the former drainage may have been originally consequent on a regional uplift of the Appalachian axis, which may have been either the late Paleozoic rise of the Appalachians, or possibly some later uplift following an unknown period of sedimentation.

Some indirect evidence, of uncertain validity, suggests drainage superposition from a former continuous sedimentary cover in at least part of the area. There is no direct evidence to support this theory, though the negative field evidence is against it; on the other hand, nothing has been found which is incompatible with such an interpretation.[8]

[8] The writer is especially indebted to Professor R. W. Whipple, of Marietta College, by whom he was first introduced to the problems here discussed, and to Professor Douglas Johnson, of Columbia University, under whose direction and with whose helpful advice most of the work has been done.

The results of the study have been presented, from time to time during the past year, to the Seminar in Geomorphology, conducted by Professor Johnson at Columbia; and the writer is likewise under obligation to various members of the seminar for many suggestions and pertinent criticisms.

IDENTIFICATION OF EROSION SURFACES IN EASTERN AND SOUTHERN OHIO[1]

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ABSTRACT

Two pronounced upland erosion surfaces are present in eastern and southern Ohio. Below these surfaces strath valleys and strath terraces are found.[2] In identifying and correlating these surfaces with other well-known surfaces, the strath stage has been neglected by previous workers. A correlation is proposed which accounts for all the erosion surfaces in this area and correlates them with other well-known Appalachian surfaces.

INTRODUCTION

Correlation of the erosion surfaces of eastern and southern Ohio and adjacent areas in Pennsylvania and West Virginia with the recognized surfaces in eastern Pennsylvania and adjacent areas has been attempted recently by Ver Steeg,[3] Fridley and Nölting,[4] and Sharp.[5] Considerable divergence of the views is expressed by these authors. This article is an attempt to present another view of the identification and correlation of these erosion surfaces in the light of information obtained by a study of projected profiles and field work.

The index map (Fig. 1) shows the area over which detailed study was made.

REVIEW OF PREVIOUS CORRELATIONS

Ver Steeg considers the upland surface which bevels the rocks of eastern Ohio at elevations varying from 1,100 to 1,400 feet equiva-

[1] For a brief review and bibliography of the present status of the Appalachian problem see K. Bryan, A. B. Cleaves, and H. T. U. Smith, *Zeit. für Geomorphologie*, Band VII, Heft 6 (1933), pp. 312–20.

[2] W. H. Bucher, " 'Strath' as a Geomorphic Term," *Sci.*, N.S., Vol. LXXV (1932), p. 131.

[3] K. Ver Steeg, "Erosion Surfaces of Eastern Ohio," *Pan-Amer. Geol.*, Vol. LV (1931), pp. 93–102, 181–92; "Erosion Surfaces of the Appalachians," *ibid.*, Vol. LVI (1931), pp. 267–85.

[4] H. M. Fridley and J. P. Nölting, Jr., "Peneplains of the Appalachian Plateau," *Jour. Geol.*, Vol. XXXIX (1931), pp. 749–55.

[5] H. S. Sharp, "The Geomorphic Development of Central Ohio," *Denison Univ. Bull.*, Vol. XXVII (1932), pp. 1–46.

lent to the Harrisburg[6] surface of Pennsylvania. Further, he notes the existence of a lower surface, the Worthington,[7] at elevations varying from 800 to 1,100 feet, which he states is coextensive with the Lexington peneplain of Kentucky. The Worthington (Lexington) surface is correlated by Ver Steeg with the Somerville plain of New Jersey and adjacent areas. Below the Worthington (Lexington) surface, Ver Steeg recognizes the existence of a pronounced strath stage, the Parker strath, but no suggestion is made regarding the correlation of this erosional stage with other known surfaces.

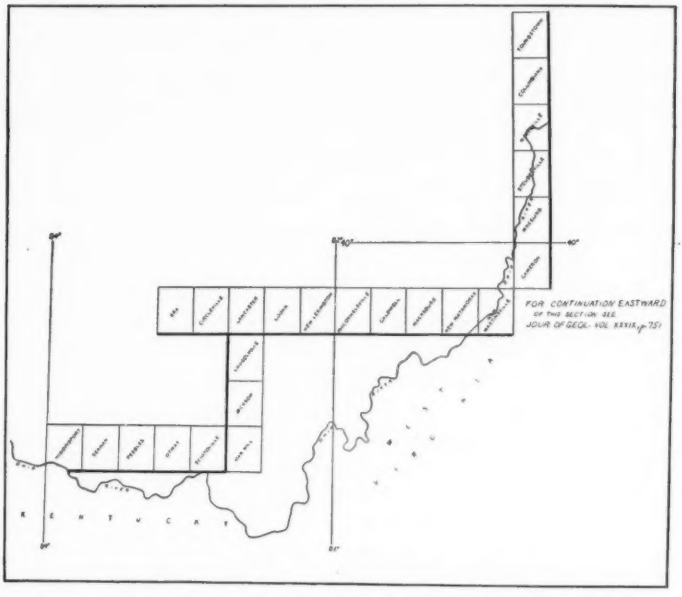

FIG. 1.—Index map. The heavy line in each section indicates the base line

Fridley and Nölting in identifying the erosion surfaces of West

[6] M. R. Campbell, "Geographic Development of Northern Pennsylvania and Southern New York," *Bull. Geol. Soc. Amer.*, Vol. XIV (1903), p. 283. Recently Campbell has suggested that the name "Chambersburg" should be substituted for "Harrisburg," *Abst.*, "Chambersburg (Harrisburg) Peneplain in the Piedmont of Maryland and Pennsylvania," *ibid.*, Vol. XLIV (1933), pp. 77, 553–73.

[7] R. W. Stone, *Topog. and Geol. Surv. Pa., 1906–08*, p. 121.

Virginia use the name "Allegheny surface,"[8] a term proposed to them by Dr. George H. Ashley for the erosion level developed in that state westward from Chestnut Ridge. This surface extends into eastern Ohio and is the same surface at the same altitudes that Ver Steeg[9] considers the equivalent of the Harrisburg erosion surface. Eastward from Chestnut Ridge these workers correlate an erosion surface developed at the 2,800–3,000-foot level with the Kittatinny peneplain.

Sharp,[10] in an article discussing the physiographic development of a section of central Ohio, gives the approximate elevations of the Harrisburg peneplain from 1,300 down to 1,000 feet within the area covered by his article. Below the Harrisburg peneplain Sharp recognizes the Worthington surface, which he considers the equivalent of the Lexington peneplain of Kentucky. These surfaces, he suggests, are the equivalents of the Somerville erosion surface, apparently overlooking the fact that this correlation had been suggested previously by Ver Steeg.[11] The existence of the Parker strath is not recognized by Sharp in his area, although it is probable that the surface of his Columbus Lowland is equivalent to the Parker strath rather than to the Worthington (Lexington) surface, as he suggests.

EROSION SURFACES OF OHIO AND WEST VIRGINIA

A detailed study has convinced the writer that there are two pronounced erosion surfaces and a major strath stage in southern and eastern Ohio. A still higher surface may be recognized in West Virginia east of Chestnut Ridge.

The writer contends that the Parker strath is the equivalent of the Somerville peneplain of New Jersey; that the Worthington (Lexington) surface corresponds with the Chambersburg (Harrisburg) peneplain; and that the highest surface of eastern Ohio, named the "Allegheny surface "by Fridley and Nölting, should be correlated with the Schooley surface of the east, as was suggested in their paper.[12]

Several competent investigators have stated that the Schooley

[8] *Op. cit.*, p. 753.
[9] *Op. cit.*, pp. 98, 99.
[10] *Op. cit.*, pp. 15–26.
[11] *Ibid.*, p. 192.
[12] *Op. cit.*, pp. 751, 754.

and Kittatinny surfaces are distinct, but Ver Steeg insists that they are one and the same.[13] If the correlation suggested by the writer is correct, it would appear that there is a surface above the Allegheny (Schooley). It may be that the name "Kittatinny" should not be applied to this surface, which may represent the remains of the warped Fall Zone peneplain.[14] Since there is a definite level above the Schooley surface, however, it seems logical to retain the name Kittatinny for this surface, as that name for the uppermost surface in the Appalachian region has become well established in the literature through the work of Barrell,[15] Bascom,[16] and others.

The correlation here suggested seems more logical than the others, because the Parker strath and the Somerville surface are alike in relative elevation and in amount of work done to produce each of them. Both the Somerville and the Parker are minor surfaces developed along the major streams and in the weaker rock. That the Parker strath is not so extensive nor so well developed as the Somerville is to be expected, considering its greater distance from baselevel control at the time of its development.

For the same reasons the Worthington (Lexington) surface should be considered the erosional equivalent of the Chambersburg (Harrisburg). The Allegheny surface is likewise the equivalent of the Schooley surface. The reasons for correlating the Allegheny surface with the Schooley have been fully considered by Fridley and Nölting[17] and need not be repeated here.

Although the Parker strath does not appear in the projected profiles because of the mechanical difficulties involved, it may be readily recognized on such topographic sheets as the Sciotoville or Waverly quadrangles. The preglacial Teays valley[18] and its tributary valleys

[13] "Erosion Surfaces of Appalachian Plateau," *Pan-Amer. Geol.*, Vol. LVIII (1932), p. 32.

[14] Sharp, "Discussion. The Fall Zone Peneplain," *Sci.*, N.S., Vol. LXIX (1929), pp. 544–45.

[15] J. Barrell, "The Piedmont Terraces of the Northern Appalachians," *Amer. Jour. Sci.*, 4th ser., Vol. XLIX (1920), pp. 338–48.

[16] F. Bascom, "Cycles of Erosion in Pennsylvania," *Jour. Geol.*, Vol. XXIX (1921), p. 544.

[17] *Op. cit.*, pp. 753, 755.

[18] W. G. Tight, "Drainage Modifications in Southeastern Ohio and Adjacent Parts of West Virginia and Kentucky," *U.S. Geol. Surv. Prof. Paper No. 13* (1903), pp. 47–72.

represent this stage. On the topographic sheets mentioned the Parker surface appears as a complete strath valley. In other places it is found only as a strath terrace, occurring above the present valley floors. The Parker surface was being developed at the time of the reversal of drainage in this area by the first glacial advance of Pleistocene time.

HIGGINSPORT-SCIOTOVILLE SECTION

Two distinct levels are noted on this section. The western level, developed at elevations between 900 and 1,000 feet with a few higher areas reaching about 1,100 feet, is the equivalent of the eastern level, developed also at elevations between 900 and 1,000 feet. In both cases the most pronounced level occurs at about 900 feet above tide. This level may be traced across Kentucky and represents the northern continuation into Ohio of the Lexington peneplain.

Between these levels there is a distinct highland level averaging about 1,200 feet. The interpretation of this upland surface is difficult. Three possibilities may be considered: (1) the highland area is a major divide on the Lexington surface and is of the same age as the lowland surfaces; (2) it is a monadnock rising above the Lexington surface; (3) it is an equivalent of the Allegheny surface that is typically developed in the eastern part of the state, but reduced slightly below the original altitude.

Although Ver Steeg[19] considers that this upland area was a continuation westward of the Allegheny surface, the writer believes it was reduced to a major divide above the Lexington surface. Because of the reduction which it must have suffered during the development of the broad, flat surfaces on either side, it should be regarded as of the same age as the bordering lowland surface.

OAK-HILL–LAURELVILLE SECTION

This section shows a gradually sloping surface which rises toward the north with the exception of a few projections. The Oak Hill–Laurelville section represents the northern continuation of the Lexington level.

Traced northward in southern and eastern Ohio, this surface becomes more restricted until it finally merges into a broad strath or strath terrace which has been termed the "Worthington."

[19] *Op. cit.*, pp. 186, 187.

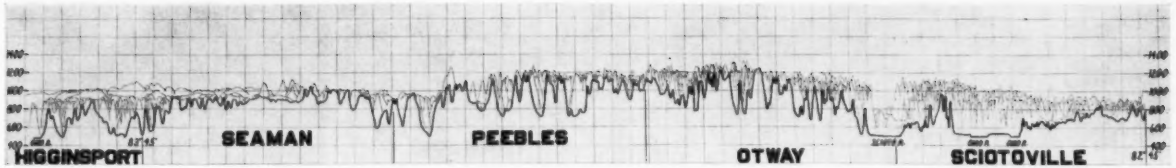

FIG. 2.—Projected profiles of Higginsport-Sciotoville section. Base line along southern boundaries of quadrangles

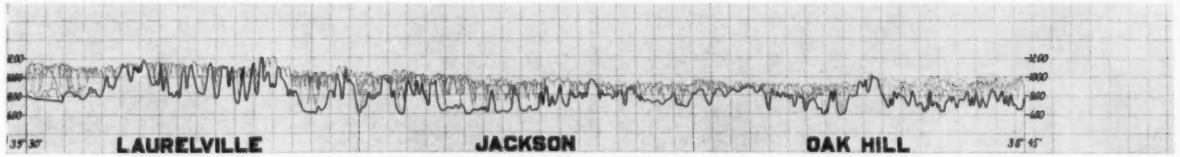

FIG. 3.—Projected profiles of Oak Hill–Laurelville section. Base line along western boundaries of quadrangles

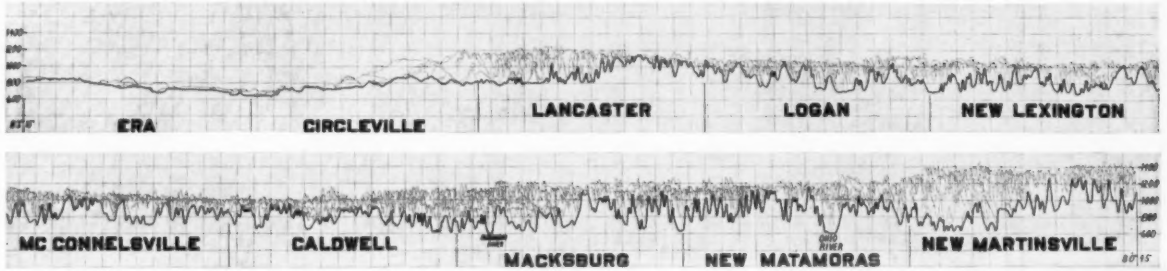

FIG. 4.—Projected profiles of the Era–New Martinsville section. Base line along southern boundaries of quadrangles

NEW MARTINSVILLE–ERA SECTION

On the New Martinsville quadrangle a distinct level averaging about 1,400 feet in elevation is observed. Westward the elevations vary from 1,000 to about 1,200 feet.

The highland area on the New Martinsville quadrangle is the continuation of the Allegheny peneplain into eastern Ohio. The broad, gently undulating surface westward is correlated with the Lexington surface, but does not record so great a reduction of the area as in southern Ohio and northern Kentucky. This surface is intermediate in character between the well-developed Lexington peneplain and the broad strath stage which marks the typical Worthington surface of east-central and eastern Ohio.

Ver Steeg[20] has considered the areas of about 1,000 feet in elevation shown on this section equivalent to the Worthington (Lexington) surface, but those areas which have elevations of about 1,200 feet A.T. he thinks represent a higher surface. It seems that during Worthington (Lexington) time sufficient reduction has taken place on these upland areas to justify correlating them with the Worthington (Lexington) stage rather than with the Allegheny. That the Allegheny surface once extended over this area is not to be doubted, but because of the reduction they have suffered even the present uplands cannot be considered as remnants of that surface.

A distinct change in elevation is noted on the projected profile of the Circleville quadrangle. The elevations on the eastern border of the Circleville quadrangle are about 1,200 feet, but on the western portion of that quadrangle they are only about 700 feet. Westward on the Era quadrangle the elevations increase to about 850 feet. As the elevations are traced farther west on the Mount Sterling and Octa quadrangles they increase to 1,100 feet.

Although this western surface has been modified by glacial drift, the writer believes that it represents the Worthington (Lexington) surface, below which complete strath valleys were developed preglacially. These strath valleys are at the present time masked and obscured by glacial drift, but where their presence is known they should be referred to the Parker stage.

The correlation of the surface of the Interior Lowland with the

[20] *Ibid.*

Worthington (Lexington) plain has been previously suggested by Hyde[21] and later discussed by Ver Steeg.[22] The pronounced escarpment seen on the projected profile is due to a marked change in rock resistance, a condition which is homologous with that on the Higginsport-Sciotoville section, already discussed.

CAMERON-STEUBENVILLE SECTION

The upland elevations vary between 1,280 and 1,480 feet on this section. This surface represents the typical Allegheny peneplain as developed in western West Virginia and Pennsylvania.

WELLSVILLE-YOUNGSTOWN SECTION

The southern part of the Wellsville quadrangle shows the typical Allegheny surface continued northward from the Steubenville quadrangle. This surface is represented northward on the Wellsville and Columbiana quadrangles as monadnock areas, which are shown on the projected profiles.

The Worthington (Lexington) surface appears from 1,100 to 1,270 feet, continuing northward on the Youngstown quadrangle at slightly lower average elevation.

This interpretation is slightly different from that originally proposed for this area by Stout and Lamborn.[23] They give the elevation of the Harrisburg (Allegheny of this paper) peneplain as approximately 1,270 feet and the Worthington as approximately 1,130 feet.

As the Worthington (Lexington) is present as a gently undulating surface in the area covered by the Columbiana quadrangle, the preceding interpretation given would seem to be more acceptable. The Worthington (Lexington) surface rises from about 1,100 feet to about 1,270 feet, and the higher areas appear above this gently sloped surface as monadnocks, the summit elevations of which may be correlated with the well-developed Allegheny surface farther south. According to the Stout and Lamborn interpretation,[24] the

[21] J. E. Hyde, "Camp Sherman Quadrangle," *Ohio Geol. Surv., Bull. 23*, 4th ser. (1921), p. 165.

[22] *Ibid.*, p. 189.

[23] W. Stout and R. E. Lamborn, "Columbiana County," *Ohio Geol. Surv. Bull. 28*, 4th ser. (1924), p. 39.

[24] *Ibid.*, pp. 38–41.

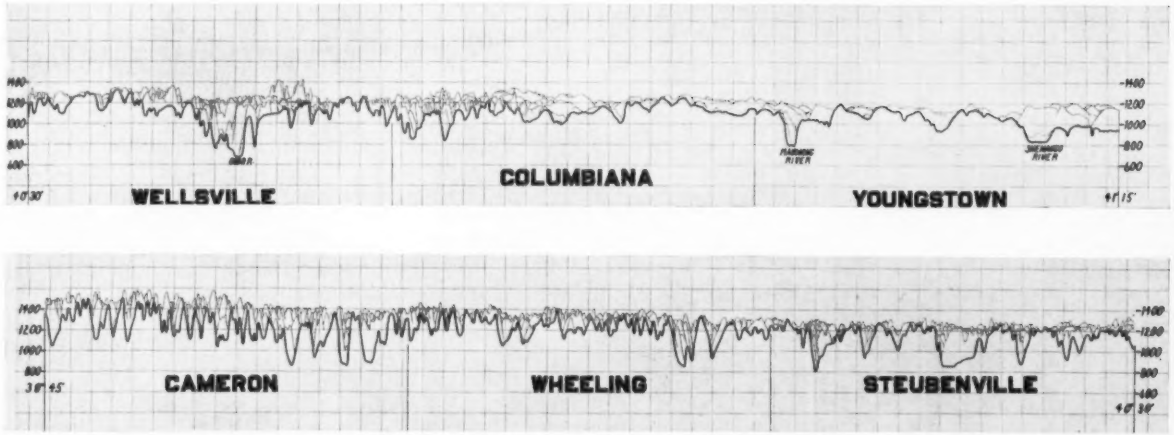

FIG. 5.—Projected profiles of the Cameron-Youngstown section. Base line along eastern boundaries of quadrangles

lower portion of this surface is assigned to a different stage from that of the upper portion. The Parker strath is present in this area as a strath terrace, but does not show on the projected profiles.

SUMMARY

Two well-marked and readily identified erosion levels are present in the area studied, with one strath stage which also may be easily recognized. The highest level present in Pennsylvania and West Virginia, the Kittatinny surface, does not appear in Ohio. Thus the highest erosion surface in Ohio should be correlated with, and be known as, the Allegheny.

Below this surface in eastern and southern Ohio the rocks are beveled by the Lexington plain, a plain which is well developed in the southern part of the state, but grades into a broad strath stage in the east-central and eastern portions. The continuation of the Lexington plain as a major strath is known as the Worthington surface.

The Allegheny surface is correlated with the Schooley peneplain of eastern Pennsylvania, and the Worthington (Lexington) level is the equivalent of the Chambersburg (Harrisburg) peneplain. Below these surfaces there is developed the Parker strath, which is the erosional equivalent of the Somerville plain.[25]

[25] *Acknowledgment.*—The author gratefully acknowledges his indebtedness to Professor O. D. von Engeln for numerous suggestions during the progress of the work and the preparation of the manuscript.

THE EVOLUTION AND CLASSIFICATION OF THE CROCODILIA

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ABSTRACT

Studies during the last fifteen years in connection with the preparation of a monograph on the fossil Crocodilia have revealed the lack of an adequate modern classification which includes an important Triassic form recently described by Mr. Barnum Brown. This article outlines a new classification of the Crocodilia into four suborders, and indicates by diagram the relations of the families of the Crocodilia, as they are interpreted by the author.

INTRODUCTION

A systematic study of the living and extinct members of the order Crocodilia has engaged the author since 1919. The study has been materially aided by grants from the Osborn Research Fund of the American Museum of Natural History. The following remarks on the evolution and classification of the major groups of crocodilians may be considered as a report of progress on this investigation.

The order Crocodilia, as the term was used by the eighteenth-century zoölogists, included only living forms. Beginning with the work of Cuvier,[2] fossil forms gradually have been included, and the content of the order has been quite different in the treatment given by various investigators.

Without attempting to deal exhaustively with the history of the classification of the group, a few examples of various usages may be given. Richard Owen[3] included three orders in the Crocodilia: the Opisthocoelia, including those forms with opisthocoelous presacral vertebrae, Mesozoic; the Amphicoelia, including Mesozoic forms with amphicoelous or amphiplatyan presacral vertebrae; and the Procoelia, including forms with procoelous presacral vertebrae, chiefly Cenozoic. Discovery of adequate material revealed the fact

[1] "Contributions to the Osteology, Affinities, and Distribution of the Crocodilia," No. 30.

[2] G. Cuvier, *Ossemen Fossiles*, Vol. V, Part 2 (3d ed., 1824), pp. 13–173.

[3] "On the Orders of Fossil and Recent Reptilia with Their Distribution in Time," *Rept. Brit. Assoc. Adv. Sci., 29th Meeting* (1860), pp. 153–66.

that the Opisthocoelia are saurischian dinosaurs (*Brontosaurus*, *Diplodocus*, etc.) only distantly related to crocodiles.

Huxley[4] included the phytosaurs and their allies in the Crocodilia, as the suborder Parasuchia. He divided the Crocodilia into three suborders: the Parasuchia, the Mesosuchia (essentially the same as Owen's Amphicoelia), and the Eusuchia (essentially the same as Owen's Procoelia). Zittel,[5] in 1890, followed this usage. The Mesosuchia were characterized by primitive form and position of the internal narial aperture, which is never entirely surrounded by the pterygoid bones. The Eusuchia were characterized by a highly specialized form and position of the internal narial aperture, which is entirely surrounded by the pterygoids. The Parasuchia are now known to be pronouncedly different from true crocodiles. They must be considered as a separate order, or members of the Thecodontia.

Later authors have in some cases followed Huxley's treatment of the Mesosuchia and Eusuchia, or have united the members of both groups under the Eusuchia. In 1902, Fraas[6] proposed the suborder Thalattosuchia to include extremely specialized marine forms such as *Geosaurus*.

A few of the later major classifications of the Crocodilia may be outlined briefly. In 1918 Zittel[7] omitted subdivision into suborders and listed the following families under the Crocodilia

Teleosauridae
Metriorhynchidae
Macrorhynchidae
Atoposauridae
Goniopholidae
Libycosuchidae
Gavialidae
Crocodilidae

[4] T. H. Huxley, "On *Stagonlepis robertsoni*, and on the Evolution of the Crocodilia," *Quart. Jour. Geol. Soc. London*, Vol. XXXI (1875), pp. 423–38, Pl. XIX.

[5] K. von Zittel, *Handbuch der Palaeontologie*, Band III, Abth. I (1890), pp. 633–89.

[6] E. Fraas, "Die Meer-Crocodilier (Thalattosuchia) des oberen Jura unter specieller Beruchtsichtigung von *Dacosaurus* und *Geosaurus*," *Palaeontographica* (1902), Band XLIX, pp. 1–72.

[7] *Grundzüge der Palaeontologie* (1918), pp. 304–17.

Williston,[8] in 1925, classified the Crocodilia as follows:

Suborder Eusuchia
- Family Teleosauridae
- Pholidosauridae
- Atoposauridae
- Goniopholidae
- Dyrosauridae
- Hylaeochampsidae
- Gavialidae
- Tomistomidae
- Crocodilidae

Suborder Thalattosuchia
- Family Metriorhynchidae

O. P. Hay,[9] in 1930, proposed the following classification:

Order Crocodilomorphi
- Suborder Goniopholidiformes
  - Family Goniopholididae
  - Pholidosauridae
- Suborder Gavialiformes
  - Family Gavialidae
  - Tomistomidae
  - Thoracosauridae
- Suborder Crocodyliformes
  - Family Crocodylidae

This classification is concerned primarily with North American forms and is not complete.

In the 1932 edition of the Zittel-Eastman[10] textbook of Smith Woodward gives the following classification:

- Suborder Mesosuchia
  - Family Teleosauridae
  - Pholidosauridae
  - Metriorhynchidae
  - Atoposauridae
  - Goniopholidae
  - Notosuchidae

[8] S. W. Williston, *Osteology of Reptiles*, pp. 287–91.

[9] "Second Bibliography and Catalogue of the Fossil Vertebrata of North America," Vol. II, Part II, *Carn. Inst. Wash. Pub. No. 390* (1930), pp. 1074.

[10] A. S. Woodward, Revision of *Text-Book of Palaeontology*, by Zittel-Eastman (1930), pp. 352–68.

Suborder Eusuchia
Family Hylaeochampsidae
Stomatosuchidae
Tomistomidae
Alligatoridae
Crocodilidae
Gavialidae

The latest classification is in the new textbook (1933) by A. S. Romer.[11] This classification involves no suborders. The following families are listed:

Teleosauridae
Metriorhynchidae
Atoposauridae
Goniopholidae
Crocodilidae

THE PROTOSUCHIA

Since this classification appeared, Mr. Barnum Brown[12] has announced a very primitive crocodilian—*Protosuchus richardsoni*—from the Middle Triassic of Arizona, for which he proposed the family name Protosuchidae.[13]

The characters of this family are distinctly crocodilian, but are sufficiently primitive to be considered subordinally distinct from all other known crocodilians. A new suborder is therefore proposed.

PROTOSUCHIA: NEW SUBORDER

Type family.—Protosuchidae Brown. Only known genus and species *Protosuchus richardsoni* Brown.

Type description.—Superior surface of cranium flattened into a cranial table; orbits directed largely outward; carpal bones elongated; pubis included in border of acetabulum, but only to a very slight extent; vertebrae amphicoelous.

This combination of characters clearly indicates true crocodilians

[11] *Vertebrate Paleontology* (University of Chicago Press, 1933), pp. 170–73, 439, 446.

[12] This form was originally named *Archeosuchus richardsoni* and the family was designated Archeosuchidae. *Archeosuchus* was preoccupied, having been used for a South African reptile by Broom. Mr. Brown has substituted the name *Protosuchus* for the genus and Protosuchidae for the family.

[13] "An Ancestral Crocodile," *Amer. Mus. Novitates, No. 638* (1933), pp. 4; "A Change of Names," *Sci.*, N.S., Vol. LXXIX (1934), p. 80.

of a very primitive stage of evolution. The relationship between this group and other crocodilians is discussed on the following pages.

SUBORDINAL AND FAMILY CLASSIFICATION

From a comprehensive study of a very large number of crocodilian forms from specimens, and nearly all known forms from the literature, it seems clear that the known living and extinct crocodilians may be grouped naturally into four major groups, which we may call

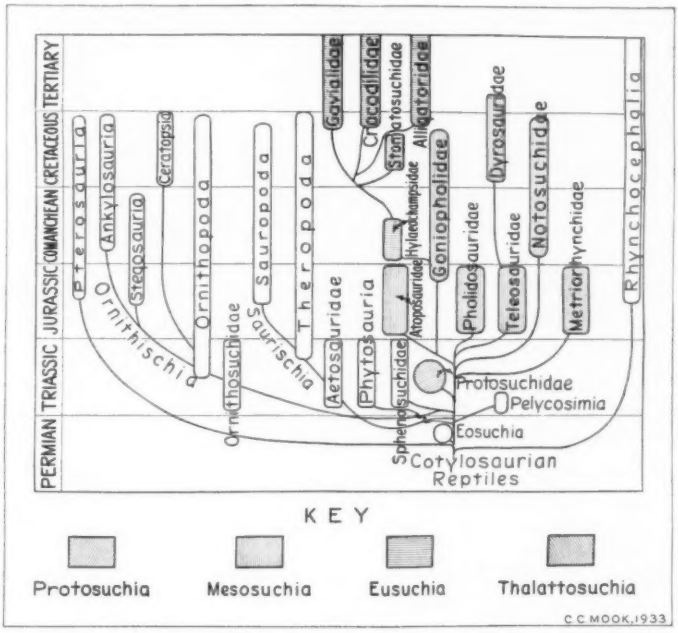

FIG. 1.—Key to the relationship of the suborders and families of the Crocodilia to each other and to other groups of diapsid reptiles, as interpreted in the present study. (Chart photographed at American Museum of Natural History).

suborders. These are the Protosuchia, the Mesosuchia, the Thalattosuchia, and the Eusuchia.

SUBORDER PROTOSUCHIA.—This suborder was defined on page 298.

FAMILY PROTOSUCHIDAE.—"Pubis forming part of acetabulum, but nearly excluded" (Brown). Triassic.

Protosuchus Brown.

SUBORDER MESOSUCHIA.—Internal narial aperture between or posterior to the palatine bones, sometimes penetrating the pterygoids, but never surrounded by them; postorbital bar usually at surface of skull and sculptured; sometimes subdermal; vertebrae amphicoelous or amphiplatyan, never procoelous; pubis excluded from acetabulum.

FAMILY TELEOSAURIDAE.—Snout elongate and slender; supratemporal fenestrae subrectangular, much larger than orbits; frontal participates in borders of supratemporal fenestrae; maxillaries meet on midline superiorly, excluding nasals from contact with premaxillaries or from entering external aperture; vertebrae platycoelous; fore limbs much smaller than hind limbs; dermal armor complete. Jurassic.

Pelagosaurus Kaup; *Teleosaurus* Geoffroy; *Teleidosaurus* Deslongchamps; *Aeolodon* Meyer; *Crocodileimus* Jourdan; *Gnathosaurus* Munster; *Steneosaurus* Geoffroy; *Mycterosaurus* Andrews; *Mystriosaurus* Kaup.

FAMILY PHOLIDOSAURIDAE.—Snout elongate and slender; supratemporal fenestrae smaller than orbits; frontal participates in borders of supratemporal fenestrae; nasals extend forward to form contacts with the premaxillaries, excluding the maxillaries from contact with each other on the midline dorsally; postorbital bar somewhat modified; internal narial aperture farther back than in Teleosauridae; vertebrae platycoelous; fore limbs relatively larger than in Teleosauridae; dermal armor complete or nearly so. Jurassic.

Pholidosaurus Meyer (*Macrorhynchus* Dunker); *Petrosuchus* Owen.

FAMILY ATOPOSAURIDAE.—Small size. Snouts short and pointed; supratemporal fenestrae smaller than orbits; external narial aperture sometimes divided; internal nares do not reach pterygoids; postorbital bar slightly modified; vertebrae platycoelous; limbs long and slender; dermal armor of two rows of dorsal plates. Jurassic.

Alligatorium Jourdan; *Alligatorellus* Jourdan; *Atoposaurus* v. Meyer.

FAMILY GONIOPHOLIDAE.—Skull short or of moderate length, and broad; supratemporal fenestrae usually smaller than orbits; frontal bone participates in margins of supratemporal fenestrae;

internal narial aperture between palatines and pterygoids; mandibular fenestra sometimes absent; postorbital bar subdermal; vertebrae platycoelous; dorsal armor of two or more rows of scutes. Jurassic to Cretaceous.

Goniopholis Owen (*Diplosaurus* Marsh; *Amphicotylus* Cope); *Coelosuchus* Williston; *Bernissartia* Dollo; *Machimosaurus* v. Meyer; *Nannosuchus* Owen; *Theriosuchus* Owen; *Oweniasuchus* Woodward (*Brachydectes* Owen); *Symptosuchus* Ameghino; *Microsuchus* de Saez; *Doratodon* Seeley; *Shamosuchus* Mook.

FAMILY DYROSAURIDAE.—Snout long and slender; internal narial aperture between palatines and pterygoids; postorbital bar subdermal. Cretacous to Eocene.

Dyrosaurus Pomel; *Teleorhinus* Osborn; *Wurnosaurus* Swinton; *Sokotosaurus* Swinton; *Rhabdognathus* Swinton; *Hyposaurus* Owen.

FAMILY NOTOSUCHIDAE.—Snout very short; quadrate bone only slightly inclined backward; internal narial aperture between palatines and pterygoids; supratemporal fenestrae smaller than orbits; preorbital fenestra sometimes present; frontal bone excluded from borders of supratemporal fenestrae; postorbital bar subdermal; mandibular fenestra very large. Jurassic? Comanchean to Cretaceous.

Notosuchus Woodward; *Libycosuchus* Stromer; (?) *Hoplosuchus* Gilmore; *Uruguaysuchus* Rusconi; *Cynodontosuchus* Woodward.

SUBORDER THALATTOSUCHIA.—Specialized marine adaptations; dermal armor, claws, and preorbital fenestrae lacking; skulls elongate; internal nares at posterior ends of palatines; sclerotic plates present; skull bones smooth; vertebrae platycoelous; limbs modified into paddles.

FAMILY METRIORHYNCHIDAE.—Skull elongate; nasals large, often in contact with premaxillaries; frontal bone participates in borders of supratemporal fenestrae; orbits directed outward and forward; sclerotic plates present; postorbital bar subdermal; vertebrae amphicoelous or amphiplatyan; long tail bent downward, with caudal fin; fore limb shortened and expanded into paddle; hind limb large; no bony armor. Jurassic.

Metriorhynchus v. Meyer (*Suchodus* Lydekker); *Geosaurus* Cuvier (*Halilimnosaurus* Ritgen), *Cricosaurus* Wagner (*Rhacheosaurus* v.

Meyer); *Dakosaurus* Quenstedt (*Plesiosuchus* Owen); *Neustosaurus* Raspail; *Enaliosuchus* Koken.

SUBORDER EUSUCHIA.—Internal nares entirely surrounded by the pterygoids, and usually near the posterior end of the latter; postorbital bar subdermal; vertebrae procoelous.

FAMILY HYLAEOCHAMPSIDAE.—Size small; skull short and broad; internal narial aperture surrounded by pterygoids; fenestra between ectopterygoid, jugal, and maxillary; vertebrae probably procoelous. Comanchean.

Hylaeochampsa Owen; (?) *Heterosuchus* Seeley.

FAMILY STOMATOSUCHIDAE.—Skull broad and flat, with elongated facial portion; supratemporal fenestrae small; frontal does not participate in their borders; orbits directed upward; slender mandible without teeth; symphysis weak; hypapophyses lacking in cervical vertebrae. Eocene.

Stomatosuchus Stromer.

FAMILY GAVIALIDAE.—Snout long and slender; nasals separated from maxillaries by union of maxillaries on dorsal midline; snout sharply separated from cranial portion of skull; orbits directed outward and forward; supratemporal fenestrae larger than orbits; splenials comprise a considerable portion of the long mandibular symphysis. Cretaceous to Recent.

Gavialis Oppel (*Leptorhynchus* Clift, *Rhamphostoma* Wagler); *Rhamphosuchus* Owen.

FAMILY CROCODILIDAE.—Snout usually broad, varying from short to long; supratemporal fenestrae small; postorbital bar subdermal; nasal bones usually reach external nares; number of teeth sometimes reduced; mandibular symphysis of moderate length; dorsal scutes in two or more rows. Cretaceous to Recent.

Crocodilus Laurenti (*Thecachampsa* Cope); *Leidyosuchus* Lambe; *Phobosuchus* Nopsca (*Deinosuchus* Holland non Gervais); *Allodaposuchus* Nopsca; *Osteolaemus* Cope; *Osteoblepharon* Schmidt; *Dinosuchus* Gervais (*Purrusaurus* Rodriguez); *Emysuchus* Nopsca; *Orthogenysuschus* Mook; *Pallimnarchus* De Vis; *Tomistoma* Müller (*Rhynchosuchus* Huxley); *Gavialosuchus* Toula and Kail; *Holops* Cope; *Eosuchus* Dollo; *Thoracosaurus* Leidy (*Sphenosaurus* Agassiz);

Gryposuchus Gürich; *Leptorhamphus* Ambrosetti; *Oxydontosaurus* Ambrosetti; *Euthecodon* Fourtau.

FAMILY ALLIGATORIDAE.—Snout short and broad; nasal bones usually reach external narial aperture; supratemporal fenestrae usually smaller than orbits, sometimes closed over secondarily; mandibular symphysis short; first mandibular teeth and usually the fourth bite into pits in palate; two or more rows of dorsal scutes. Cretaceous to Recent.

Alligator Cuvier; *Diplocynodon* Pomel; *Bottosaurus* Agassiz; *Brachychampsa* Gilmore; *Brachygnathosuchus* Mook; *Allognathosuchus* Mook; *Proalligator* Ambrosetti; *Caiman* Spix; *Jacare* Gray; *Eocaiman* Simpson.

ORIGIN AND EVOLUTION OF CROCODILIAN FAMILIES

The Crocodilians are diapsid reptiles and are obviously related to other diapsid groups. Broom and von Huene[14] have both pointed out characters in *Sphenosuchus* which might evolve into crocodilian characters. *Sphenosuchus* itself is definitely a Pseudosuchian and cannot well be considered directly ancestral to the Crocodilia.

Protosuchus of Brown, from the Middle Triassic of Arizona, is well fitted to serve as an ancestral crocodilian. The cranial table, the arrangement of the scutes, the form of limb, carpal, pelvic bones, and ribs are distinctly crocodilian. The slight participation of the pubis in the acetabulum is not shared by other crocodilians, but it is a primitive diapsid character, and is exactly what one would expect in an ancestral crocodilian.

The position of the orbits is reminiscent of pseudosuchians, and may well be considered a heritage from pseudosuchian ancestry. Because of this heritage, and because of the fact that the key structures of the palate cannot be made out in the type specimen, the author believes *Protosuchus* should be placed very near the line of direct ancestry of the later crocodilians but may not actually be in that line.

[14] R. Broom, "On *Sphenosuchus*, and the Origin of the Crocodiles," *Proc. Zoöl. Soc. London* (1927), pp. 359–70; F. von Huene, "Die Bedeutung der Sphenosuchus-Gruppe für den Ursprung der Krokodile," *Zeitschr. für Ind. Abstam. und Vererb.*, Vol. XXXVIII (1925), pp. 307–25.

The Crocodilia must have evolved from unknown *Sphenosuchus*-like pseudosuchians in late Permian or early Triassic time. The earliest members of the group must have resembled *Protosuchus* rather closely, and should probably be included in the Protosuchia.

In middle and late Triassic time protosuchian ancestors must have given rise to evolutionary lines that we recognize in more complete development in the Jurassic mesosuchian families Teleosauridae, Atoposauridae, and Pholidosauridae, and also the Jurassic thalattosuchian family Metriorhynchidae.

The Jurassic to Cretaceous Goniopholidae evidently branched from common stock nearer to the atoposaurids than to the teleosaurids and pholidosaurids. The Notosuchidae are a side line of Comanchean and Cretaceous mesosuchians that evidently branched off from the protosuchian stem independent of other mesosuchians. The Dyrosauridae represent a Cretaceous and early Tertiary line similar in some respects to the teleosaurids and evidently evolved from that group.

The most primitive Eusuchians are obviously the Hylaeochampsidae. This group possesses distinctive eusuchian characters, and yet is primitive. It is evidently derivable from a goniopholid ancestry. Its characters, together with its geologic horizon (Wealden), fit it admirably to serve as a group ancestral to the later eusuchians.

Of the later eusuchians the Stomatosuchidae, of the Cretaceous, is definitely a side line, and is not so closely related to the three living families as they are to each other.

The Gavialidae, Crocodilidae, and Alligatoridae are evidently derivable from a hylaeochampsid stock, and have been evolving independently since late Cretaceous times.

A NEWLY FOUND METEORITE FROM LANTON, HOWELL COUNTY, MISSOURI

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Missouri School of Mines and Metallurgy

ABSTRACT

The Lanton meteorite is one of the usual type of nickeliferous irons. It is an outstanding example of the way in which large masses of meteoritic iron may be broken up by differential oxidation. The subsequent scattering of the pieces may give the impression that the mass was broken by the force of impact at the time of the fall.

The Lanton meteoric iron, consisting of four separate fragments, was found during the first week of July, 1932, by Mr. R. A. Newcomb, on his farm ½ mile northwest of Lanton. The discovery was brought to the attention of one of the authors on July 22, by Mr. G. J. Farrell of West Plains, Missouri, who had obtained a small piece of one of the fragments. The locality was visited July 24, and although the field where the fragments were found was carefully searched, no more could be discovered.

The several fragments were found lying on the surface of the ground within an area about 6 feet in diameter, near the top of the slope on the southeast side of a small drain. The exact location is about 40 feet south of the middle of the north line of the NW.¼ SE.¼ Sec. 35, T.22 N., R.8 W. The fragments have been numbered according to their weights and will be referred to by number as follows:

Fragment No. 1		8,930 gms.
Fragment No. 2	Approx.	2,730 gms.
Fragment No. 3		760 gms.
Fragment No. 4—(includes 3 pieces)	Approx.	1,360 gms.
Total weight	Approx.	13,780 gms.

Fragment No. 1 is now in possession of the Missouri Bureau of Geology and Mines at Rolla, Missouri. Fragment No. 2 which had been heated in a blacksmith's forge at Lanton, is in possession of Maney Nale, the blacksmith, with the exception of the small piece given to the authors by Mr. Farrell. Fragment No. 3 was given to one of the authors by Mr. Newcomb at the time the fall was first investigated. Fragment No. 4 was retained by Mr. Newcomb.

The exterior of each of the fragments is dark reddish-brown in color and consists almost wholly of iron oxide, which forms a crust or veneer of variable thickness over the entire surface. Along the cleavage planes and fractures oxidation has penetrated to greater depths. Continued oxidation along lines of weakness resulted in disintegration of the mass, as exemplified by fragment No. 4, which was intact when found, but was easily separated into several parts.

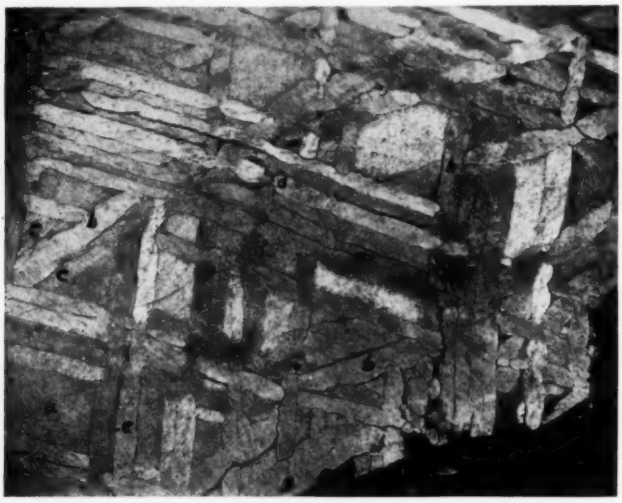

FIG. 1.—Polished surface of part of fragment No. 3, showing rhombic plessite areas (*a*), thick lath-like bands of kamacite (*b*), very thin bands of taenite (*c*), and irregular areas tentatively designated as schreibersite (*d*). In the specimen the taenite appears silver white. ×3.

In view of the behavior of fragment No. 4 it is thought that the original fall probably consisted of a single mass, which subsequently has been reduced to a number of smaller fragments by oxidation along lines of weakness. The fact that they were all found in such a limited area lends further weight to this conclusion. It does not seem plausible that four fragments would fall so close together; neither does it seem plausible that a metallic mass would break or shatter upon impact with the soil. The slight scattering of the fragments may very well be due to cultivation of the field before the mass was

recognized as a meteorite. Such disturbance would also accelerate the disintegration and bring the fragments to the surface.

The internal structure of the material has been determined by a study of fragment No. 3, which was sawed into four pieces for this purpose. One face of each piece was polished and then etched with a solution of one part concentrated nitric acid in ninety-nine parts of ethyl alcohol. This etching solution has proved more satisfactory

FIG. 2.—Polished surface of fragment No. 3, showing kamacite bands ending against a plessite area, which contains thin stringers of taenite. A few large black areas tentatively called schreibersite are also seen surrounded by taenite. ×75.

than others, because the absence of water eliminates much of the oxidation.

A megascopic examination of the polished and etched surface reveals a number of intersecting bright bands, bounding dull polygonal areas, commnly known as Widmanstätten structure (Fig. 1).

Etching brings out a beautiful pattern of rather uniform kamacite plates averaging less than a millimeter in width. These plates are separated by very thin shiny plates of taenite (Fig. 1). A number of

measurements show them to range from a minimum of 0.02 mm. to a maximum of 0.08 mm. in width. Many of the taenite bands split and enclose small areas of an undetermined substance resembling schreibersite (Fig. 2). This suggestion is supported by the chemical analysis, which shows 0.18 per cent phosphorus. Irregularly distributed throughout the mass are numerous rhombic or roughly triangular areas of plessite (Fig. 1), a mixture of kamacite and taenite. These plessite areas are of several types: (*a*) those showing no structure and exhibiting what may be called a sand-blast finish; (*b*) granular; (*c*) parallel-laminated; and (*d*) combinations of the preceding.

A partial chemical analysis furnished by W. T. Schrenk and Warren B. Danforth, of the Department of Chemistry of the Missouri School of Mines and Metallurgy, yielded the following:

Fe	90.40
Ni	8.33
Co	0.61
P	0.18
SiO_2	0.005
Mn	none
Cu	none
Total	99.525

AMBER IN CALIFORNIA

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ABSTRACT

A fossil resin recently discovered in the Eocene strata of California has been determined as true amber. This is the first recorded occurrence of this material in California. Associated with it are various plant remains, including some fossil wood, which, however, does not seem to have been the source of the amber.

Some resinous material from the Eocene of California has been examined by the writer and identified as amber. So far as he knows, no amber has been reported from this region. Mr. Frank Tolman,[1] through whose courtesy the specimen was examined, gives the locality and stratigraphic horizon as follows:

The particular piece of amber under discussion was found on the northeast side of Simi Valley, California, in the southwest corner of the Santa Susana quadrangle, 3,600 feet N. 43° E. from the Marrland Country Club house. The formation exposed here is the Llajas,[2] considered by B. L. Clark[3] to be Domengine. However, several faunal horizons occur in the Llajas, some older and some younger than the fauna of the type Domengine. The horizon from which the amber came is approximately 920 feet above the base of the Llajas, in a dark-gray, clay shale just below the lowest stratigraphic occurrence of *Discocyclina cloptoni* Vaughan. This is the highest occurrence stratigraphically at which amber has been found in the Eocene section of the northeast side of Simi Valley, though fragments of amber were noted in well cores and in outcrop samples throughout the lower part of the Llajas section down to the basal conglomerate, i.e., from 300 feet above the base of the Llajas to 920 feet above it. Throughout this same portion of the section fragments of fossil wood full of borings also occurred.

The fossil wood to which Mr. Tolman refers was suspected of being the source of the amber, and accordingly some thin sections

[1] Private communication.

[2] J. H. McMasters, "Eocene Llajas Formation, Ventura County, California (Abstract)," *Bull. Geol. Soc. Amer.*, Vol. XLIV, No. 1 (1933), pp. 217–18.

[3] "The Domengine Horizon, Middle Eocene of California," *Univ. Calif. Publ. Bull. Dept. Geol.*, Vol. XVI, No. 5 (1926), pp. 109–10. See also R. B. Stewart, "Gabb's California Fossil Type Gastropods," *Proc. Acad. Nat. Sci. Phila.*, Vol. LXXVIII (1926), pp. 287–447.

of it were made and sent to Professor R. W. Chaney, of the University of California, for inspection. Unfortunately, though some of the slides showed unmistakable flecks of amber, the wood which was determinable was not coniferous. It is possible, however, that some lignite, which showed no recognizable structure, may have been the source. One of the sections proved to be an oak, and another "a heavy dicotyledonous type, possibly a legume."[4]

This occurrence is interesting in that the amber occurs in rocks older than those which furnish the famous Baltic amber (Oligocene). Still older amber is known, however, and one of the few occurrences noted for Western North America is of Cretaceous age.[5]

The following comparison of the properties of this California amber with those of succinite (amber), given in Dana's *System of Mineralogy*, will show its essential identity with typical material. Not enough of the new amber was available for quantitative analysis; but other tests, and a qualitative distillation, seem to be sufficiently conclusive.

	Simi Amber	Succinite
Color	Brown to honey transparent	Yellow, reddish, brownish transparent to translucent
Hardness	2.5	2–2.5
Specific gravity	1.06–	1.050–1.096
Refractive index	1.545±	1.530–1.543
Fusibility	1–	200°–300° C.

The Simi amber burns with difficulty, leaving a black, brittle residue. It is partially soluble in ether. On distillation, the presence of succinic acid was revealed by the accumulation of a white solid in the neck of the retort. This was accompanied by a reddish-brown, oily liquid, and by a more volatile, yellowish-green distillate which condensed to a thinner liquid farther from the retort.

[4] Private communication from Professor Chaney.

[5] A. W. G. Wilson, "Coalmont Amber," *Summ. Rept. Can. Mines Branch*, 1921, pp. 1, 2.

STRUCTURAL FEATURES IN THE COLUMBIA RIVER LAVAS OF CENTRAL WASHINGTON

A CRITICISM

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In his recent paper[1] with the foregoing title, Dr. Malvin G. Hoffman describes some of the identical structures that I studied in detail a few years ago. The views that he expresses on their various modes of origin are, in almost all instances, diametrically opposed to my findings. I have but little to add to the major points of the field and petrographic evidence which I gathered during the course of four years. The score of photographs which accompanied my publications[2] were well reproduced. Since the testimony of these illustrations and the reasons given for reaching my conclusions were both largely ignored by Dr. Hoffman, it is desirable to call attention to some of the essential facts that fail to coincide with his interpretation. To clarify the nature of the problem I will repeat my major thesis.

Many of the basaltic flows in the vicinity of Moses Coulee have developed basal facies either of glassy breccias or of ellipsoidal lava. In either instance each horizon retains a relatively uniform thickness of usually 25–100 feet. The breccias characteristically contain tongues and elongate ellipsoidal masses of lava which, as a rule, are roughly parallel and inclined at approximately 30°. In brief, I found that fluid lava, on advancing into shallow ponds and lakes along the margin of the lava field, had tended to granulate like molten slag upon contact with water, forming thereby a relatively fine, glassy

[1] "Structural Features in the Columbia River Lavas of Central Washington," *Jour. Geol.*, Vol. XLI (1933), pp. 184–95.

[2] M. A. Peacock and R. E. Fuller, "Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau," *Amer. Miner.*, Vol. XIII (1928), pp. 369–83; R. E. Fuller, "The Aqueous Chilling of Basaltic Lava on the Columbia River Plateau," *Amer. Jour. Sci.*, Vol. XXI (1931), pp. 281–300; "Tensional Surface Features of Certain Basaltic Ellipsoids," *Jour. Geol.*, Vol. XL (1932), pp. 164–70; "Concerning Basaltic Glass," *Amer. Miner.*, Vol. XVII (1932), pp. 104–7.

breccia. As the liquid lava poured into the water, the breccia presumably accumulated like the deposits of a delta, in which the foreset bedding was defined largely by the tongues of lava which failed to granulate as they ran down the slope, thus indicating the angle of repose of the fragments. The local failure to granulate was presumably due to irregularities either in the fluidity of the lava or in its rate of flowage, these characteristics being of course largely interdependent. On the approximately level upper surface of this accumulation, the flow would have gradually advanced, as if on dry land, thus bearing a direct analogy to topset beds.

The horizons exhibiting pillow structure were formed in a similar manner by the advance of relatively viscous flows into local bodies of water. The degree of viscosity was probably sufficient to cause the subaerial development of membranous surfaces on the advancing tongues of lava. On reaching the edge of the water, the increased gradient at the brink of the accumulation of chilled lava presumably caused the detachment of gigantic drops from the margin of the advancing flow. These would have plunged into the water and would have settled to a roughly horizontal inclination. Prior to their solidification, the explosive effect of the generated steam would have aided in the subdivision of these ellipsoidal masses, while the chilling of their surfaces would have tended to prevent them from welding together. When these spheroidal masses had accumulated to the depth of the water, the parent flow would have advanced above them almost as if on dry land. The fact that the ellipsoidal facies and the "foreset bedded breccias" are both found intimately associated in the same horizons testifies to the similarity in their modes of origin, but the difference in results is considered to depend principally on the degree of fluidity of the lava.

Dr. Hoffman believes[3] that the absence of water stratification in these breccias precludes the possibility of any aqueous agency. To my mind, however, no classification dependent on the differential rate of settling would be expected, for even the finest particles of the breccia are rarely less than 2 mm. in diameter and are considerably too coarse to permit their suspension in water. Disregarding this fact, I doubt if the explosive violence of the rising steam would have

[3] *Op. cit.*, p. 191.

permitted the development of lacustrine stratification adjacent to the margin of the gradually advancing flow.

In describing these breccias, he states[4] that "maximum dips of this apparent cross bedding are as high as 30°. A few showed dips as low as 9° or 10°. An example of the latter is located at the mouth of Douglas Creek Canyon (Fig. 1). The dip now measures 15°, but

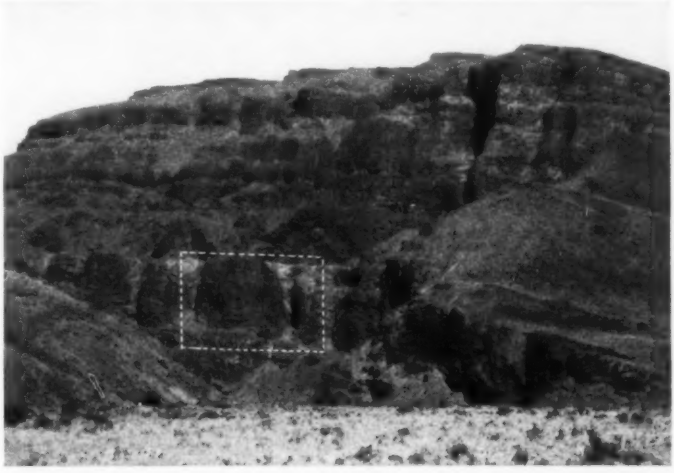

FIG. 1.—Looking toward the northeast into the mouth of Douglas Canyon from the floor of Moses Coulee. The steep exposure in the foreground on the right is formed of the palagonitic breccias to which Dr. Hoffman must have referred. Owing to the rapid increase in the southeast dip of the series as the coulee is approached, the tongues of lava, which are here cut approximately parallel to the strike of their "foreset bedding," show a marked inclination toward the coulee. At the bend of the valley, in the center of the picture, this same horizon exhibits clearly the relation of the "foreset bedding." A detailed view of the portion outlined is shown in Figure 2.

tilting subsequent to extrusion accounts for 6° or 7°." My critic at that locality happened to be observing an outcrop that is cut almost parallel to the strike of the "foreset bedded breccia." He could have seen the true slope of the inclined structure and its relation to the flow on which it rests if he had only glanced a few hundred yards upstream along the continuous exposure of that horizon (Fig. 2).

[4] *Ibid.*, pp. 189–90.

In referring to the ellipsoidal lavas, Dr. Hoffman states:[5]

Fuller assumes that all the ellipsoidal lavas in the region were formed under water, upon which he bases his statement that lakes existed at the time of their extrusion. This appears to be founded on the idea that pillow structure can only be developed when the lava is quickly quenched as a result of being poured into water. Neither the studies by Lewis nor the field evidence substantiate this assumption. The Douglas Canyon sediments are distinctly subaqueous and direct-

FIG. 2.—Detailed view of the "foreset bedded breccias" and pillow lavas in the area outlined in Figure 1. The somewhat irregular contact of the two phases is defined by the dotted line. The usual slope of approximately 30° has here been reduced by subsequent tilting. The inclined surface of the lower flow is indicated by the dashed line.

ly overlain by basalt which is not ellipsoidal. Fuller remarks the absence of pillow structure at this locality even though he attempts qualification by stating that a suggestion of ellipsoidal structure exists. This is the only locality in the Moses Coulee area where there is some basis for the implication that a body of water of some sort probably existed at the time of the extrusion of the lava.

The beginning of that passage gives the reader the false impression that the former presence of water was implied merely by the development of ellipsoidal structure, and thereby neglects the evidence by

[5] *Ibid.*, p. 191.

which that conclusion was reached. Even Lewis, in the very paper which Dr. Hoffman notes, granted the probability of pillow lavas forming in the manner to which I testify.[6] Since this fact has apparently been overlooked, it is necessary for me to quote the paragraph to which I previously referred.

> The falling away of pendulous ellipsoidal masses as the lava slowly drops over a cliff, as observed by Green in Hawaii, may also produce separate individuals if their outer crusts become sufficiently hardened to prevent the welding of the masses together. This condition would probably prevail wherever the masses fall into water, although under favorable conditions of temperature and rate of flow the presence of water would not be necessary.[7]

Although I grant that water might not be necessary thus to attain the separation of the pillows, aqueous chilling is, to my mind, essential if we are to explain the rapid quenching demanded by the formation of their heavy vitreous coating, which we both have recorded.

Granting that the Douglas Canyon sediments are subaqueous in deposition, I again state that in the northern portion of the exposure cross bedding and even mud cracks[8] indicate near-shore deposition and a seasonal fluctuation of the water. Well-developed ripple marks subsequently observed in the same locality substantiate the testimony. These facts, together with the inclusion of micaceous sediments and carbonaceous material[9] in the overlying flow, all suggest that that portion of the lake was, at the most, little better than a mud flat when it was covered by the advancing lava. Several hundred yards down the valley the ellipsoidal structure is well-defined. From this locality a photograph of an isolated ellipsoidal mass immersed in soft sediments has already been published.[10] Even in the northern portion, however, it is difficult for me to understand how Dr. Hoffman failed to observe "a suggestion of ellipsoidal structure" at the base of the overlying flow. Beneath a picture of this part of the contact, I commented[11] on the ellipsoidal tendency. This precise locality has even been included in a slightly more general view printed subsequently in a paper by Arnold D. Hoffman,[12] but a close-

[6] "The Aqueous Chilling of Basaltic Lavas, etc.," *op. cit.*, p. 293.

[7] J. Volney Lewis, *Geol. Soc. Amer. Bull.*, Vol. XXV (1914), p. 649.

[8] *Ibid.*, p. 295. [9] *Ibid.*, p. 299. [10] *Ibid.*, p. 298. [11] *Ibid.*, p. 294.

[12] "The Douglas Canyon Flora of Central Washington," *Jour. Geol.*, Vol. XL (1932), p. 763.

up (Fig. 3) of the identical structure is apparently necessary to substantiate my testimony.

Dr. Hoffman's last sweeping statement in the paragraph is presumably based on the assumption that an accumulation of sediments forms the only criterion for the former presence of a body of water. Actually, in the short time interval between successive eruptions, sediments would have been able to advance from the adjacent high-

FIG. 3.—Detailed view of the basal contact of the flow overlying the Douglas Canyon sediments. The "suggestion of ellipsoidal structure" is clearly shown. The soft micaceous sediments have been squeezed between the basaltic lobes, which are selvaged with glass.

lands only a short distance upon the relatively level surface of the lava plain, and their accumulation would be very local. I have already pointed out in a previous page that stratification would not be expected to occur in the basal breccias, but it is well defined, however, at the summit of a butte of palagonitic breccias on the southern side of Moses Coulee about 4 miles from its mouth. There, as in the lowest flow at Douglas Creek, very fluid lava apparently encountered a sufficient depth of water to permit the flow locally to be completely submerged so that the finest particles of the resulting granulated

glass had been able to settle under typical lacustrine conditions without the customary covering of a parent flow. A minor locality also occurs on the eastern wall of the Columbia River Valley, about a half-mile north of Moses Coulee. Here a thin bed of stratified palagonite rests on the surface of a flow, while the lower contact of the overlying flow shows ellipsoidal structure (Fig. 4).

FIG. 4.—At the level of the pick this picture shows a thin bed of stratified palagonite which is exposed on the eastern wall of the Columbia River Valley at about half a mile north of the mouth of Moses Coulee. In the upper portion of the picture, the lower contact of the overlying flow exhibits ellipsoidal structure.

Additional testimony on this point is, however, furnished by other observers. Aaron C. Waters[13] noted many localities where the "basalts are separated by thin beds of shale or sandstone with remarkably developed paper-thin stratification that appear to have been laid down in lakes dammed along the margin of the lava field by the encroaching flows." He also records[14] that a well drilled at

[13] "The Geology of the Southern Half of the Chelan Quadrangle, Washington," doctorate thesis submitted to Yale University (1930), p. 183.

[14] *Ibid.*, p. 184.

Waterville, about 20 miles northeast of the mouth of Douglas Creek, in reaching a depth of 570 feet encountered five layers of sediments interstratified with the basalt. One of these is made up partly of sideromelane and palagonite tuffs. Even in the course of a rapid reconnaissance across this area, I. C. Russell noted[15] that wells of less than half that depth testified to the interbedding of basalt with thin layers of sediment.

In attempting to refute the rôle of aqueous agencies in the development of the basaltic structures, Dr. Hoffman made no mention of the following facts, which have already been recorded.

1. Sideromelane, the vitreous, translucent variety of basaltic glass, which forms the breccia and also coats the pillows with a thick selvage, requires excessive chilling. Except for the rare instances when it is found as a thin film on the slaggy surface of flows, its occurrence has, as a rule, been attributed to aqueous or glacial agencies.[16] In this regard, however, Dr. Hoffman adds to his difficulties by claiming that the glassy surface of the ellipsoids is 1–2 inches in thickness,[17] though I have recorded[18] less than half that figure. The discrepancy between our observations is probably due to the fact that the penetration of the water has accentuated the chilling adjacent to the major joint cracks and has thereby resulted in a superficial coating of glass on the margin of many of the blocks.[19]

2. Field evidence[20] indicates that the extensive hydration of the sideromelane to palagonite was due to the effect of the steam generated by the chilling of the lava and not to subsequent agencies. Where the breccia was protected by its contact with sediments or at the end of a flow where the escape of steam was no longer retarded by an overlying layer of lava, the brecciated glass is unaltered. This

[15] "A Geological Reconnaissance in Central Washington," *U.S. Geol. Surv. Bull. 108* (1893), p. 85.

[16] W. Sartorius von Walterhausen, *Ueber die Vulkanischen Gesteine in Sicilien und Island und Ihre Submarine Umbildung* (Göttingen, 1853), pp. 202–4; J. Murray and A. F. Renard, *Report on Deep-sea Deposits, Based on the Specimens Collected during the Voyage of H.M.S. "Challenger" in the Years 1872–76*, (London, 1891), pp. 299–311; M. A. Peacock, "The Petrology of Iceland," Part I, "The Basic Tuffs," *Trans. Roy. Soc. Edinburgh*, Vol. LV (1926), pp. 56–60; M. A. Peacock and R. E. Fuller, *op. cit.*, pp. 371–74.

[17] *Op. cit.*, p. 188. [18] "Concerning Basaltic Glass," *op. cit.*, p. 106.

[19] "Tensional Surface Features of Certain Basaltic Ellipsoids," *op. cit.*, p. 169.

[20] "Concerning Basaltic Glass," *op. cit.*, pp. 104–5.

suggestion of syngenetic alteration is strengthened by the subsequently observed fact that the palagonitization of the breccia is more intense adjacent to the lower surface of the larger isolated lava masses which would have obstructed the superheated steam from rising. Dr. Hoffman, however, offers no explanation of this localization of alteration, and in fact he refers to the palagonite merely as "weathered glass."

3. A complete chemical analysis[21] of the sideromelane from the breccia exposed east of the Columbia River about 3 miles south of the mouth of Moses Coulee records a total content of water of merely .30 of 1 per cent and the presence of no other gaseous constituents. In spite of this fact, the scoriaceous character of the glass indicates locally a large, but variable, volatile content; and many of the fragments give evidence of explosive action.

4. The coating of sideromelane which locally lines the vesicles testifies to the admixture of exotic volatiles[22] that actually chilled the lava.

5. The occurrence[23] of spiracles or vertical gas vents locally rising through a flow from its base also points to the escape of steam imprisoned beneath the lava.

6. The fossil flora[24] indicates a humid climate which demands at least seasonal precipitation. The gradual extension of the vast lava field would have resulted in the derangement of the drainage from the adjacent highlands and at the same time would have developed a youthful topography conducive to the recurrence of lakes at successive horizons.

Space does not permit a discussion of the intricacies of Dr. Hoffman's hypothesis for the subaerial origin of these structures by a process of mechanical division and brecciation of the flows. If it is even assumed, however, that the theory is plausible, a consideration of the laws of chance would hardly permit one to accept, as valid, the fortuitous recurrence in the same locality of a complex association of unsubstantiated hypotheses. As I have previously stated, his interpretation makes no attempt to explain the evidence of chilling,

[21] M. A. Peacock and R. E. Fuller, *op. cit.*, p. 371.

[22] Fuller, "Aqueous Chilling of Basaltic Lava on the Columbia River Plateau," *op. cit.*, p. 286.

[23] *Ibid.*, p. 299.

[24] A. D. Hoffman, *op. cit.*, p. 738.

although the constant occurrence of glass is recorded. Instead, it is rendered more difficult to understand by the fact that the flows are considered to be unusual in that "the upper layers of the lava moved faster than the lower layers."[25] Since Dr. Hoffman attributes the chilling to subaerial agencies it would seem to be more consistent to expect the surface lava to have attained far greater viscosity than the more insulated central portion of the flow.

The velocity of flowage, which plays an important part in the theory, seems to be largely dependent on the force of extrusion rather than on gravity. The motive power is especially obscure in the following passage:

> To develop the high-angle "cross bedding" it is necessary to carry each successive sheet of lava forward until, nearly or entirely solidified, it was pushed over the end of the flow. The shattered rock would roll down the slope at the end of the lava flow, coming to rest at an angle of repose of approximately 30°.[26]

On the contrary, instead of being "nearly or entirely solidified" when it reached the end of the flow, the characteristics of the lava that composes the "foreset bedded breccias" testify invariably to the extraordinary fluidity which the lava retained until the moment of solidification.

In closing, I wish to record the fact that neither Aaron C. Waters[27] nor I, in our extensive work in that vicinity, have ever observed any of the dikes that play such an important part in Dr. Hoffman's hypothesis on the probable manner of extrusion of the local basaltic series. The inclination of the "foreset bedding" of the breccias indicates that the flows in that region had advanced predominantly from the south and southeast.

REPLY

MALVIN G. HOFFMAN
State College of Washington

Most of the points for discussion raised by Dr. Fuller probably will not be settled until considerably more study is given to extrusive rocks over widely distributed areas. In my paper[28] I did not attempt to apply my conclusions to the origin of ellipsoidal and brecciated basalts in general, but only to those which occur in the Columbia Plateau, particularly those in central Washington. Dr. Fuller has

[25] *Ibid.*, p. 193. [26] *Ibid.*, p. 194. [27] *Op. cit.*, pp. 182–83. [28] *Op. cit.*, pp. 184–95.

described these structures and given a number of reasons for believing that they were formed by contact with water in lakes and ponds. The many exposures of these structures, however, would necessarily imply that the area in question was pretty well covered by water.

Dr. Fuller points to a few small isolated examples of stratified breccia as evidence that lakes existed. Figure 4 of his criticism is presented to show some "stratified palagonite." If the lines represent stratification planes in palagonite, I can agree with him that they were formed by the action of water.

Figures 1 and 2 in Dr. Fuller's criticism do not show the locality where I measured the low angle dip in the "foreset beds" of the basalt breccia. The breccia in the "foreset bedded" flows is not stratified. This is admitted by Dr. Fuller, who states that it was formed as the " . . . . fluid lava on advancing into shallow ponds and lakes along the margin of the lava field had tended to granulate like molten slag upon contact with water. . . . ." Since the chilling and brecciation of the lava were effected by water, it follows that the brecciation occurred at the time of encountering the water. If brecciation was effected in any part of the flow which was not covered by water this would be due to subaerial chilling and would be contrary to Dr. Fuller's hypothesis. Dr. Fuller also states that stratified breccias would occur where there was " . . . . a sufficient depth of water to permit the flow locally to be completely submerged so that the finest particles of the resulting granulated glass had been able to settle under typical lacustrine conditions." But he has already stated that the unstratified breccia was formed when the fluid lava advanced into shallow lakes and ponds and was shattered upon contact with the water, which also implies submergence. Dr. Fuller seems to be contradicting himself. His methods for the formation of both the stratified and unstratified breccia seem to be essentially the same.

Dr. Fuller states that " . . . . the horizons exhibiting ellipsoidal structure were formed in a similar manner by the accumulation of pendulous masses which had fallen into the water from the margins of the more viscous flows." Cross sections of the flows in the canyon walls exhibit ellipsoidal beds a mile and even more in extent. There are many such exposures. How could "pendulous masses" falling from the margin of a flow cover such a wide area? Probably not all

the sections are cut parallel to the edges of the flows. Such, certainly, could not be the case where an ellipsoidal bed can be traced along the main channel and also up a tributary canyon nearly at right angles to the main channel.

In one of his articles Dr. Fuller[29] writes that many of the pillows are connected by short necks and that their orientation indicates the direction of the flow. If the ellipsoids were really pendulous masses which fell from the margins of flows, it does not seem reasonable that they should now be connected by short necks, nor that most of them should have fallen in the same way so as to be oriented after reaching the water.

Dr. Fuller regards the glassy selvages on the pillows as having been formed by rapid chilling occurring upon contact with water. The implication is quite clear that the "pendulous drops" of lava must have been entirely liquid when they fell from the margin of a flow and that the glassy coat was developed very quickly after the lava reached the water. This interpretation is also necessary because Dr. Fuller is not willing to admit that cooling in air can be sufficiently rapid to produce the glassy coating. If the lava was still fluid, why did it stop flowing? Why did it cease to progress by flowage and begin to cast off pendulous masses? But Dr. Fuller also has said that when the fluid lava advanced into the shallow lakes it granulated like molten slag. Why, then, did not these pendulous drops of liquid lava granulate like molten slag?

The quantity of water already present in a magma in the form of gas, and its possible effects, have apparently been overlooked by Dr. Fuller. Day and Shepherd[30] believe that the gases collected from Kilauea, of which water vapor is most abundant, are magmatic. F. W. Clarke[31] is of the same opinion and remarks:

> It has long been held by nearly all authorities that water vapor or steam is the most abundant of the volcanic gases. The statement is generally accepted that it forms as much as 99 per cent of the entire gaseous output, but it soon condenses to liquid and is added or restored to the hydrosphere.

[29] "The Aqueous Chilling of Basaltic Lavas, etc.," *op. cit.*, pp. 281–300.

[30] Arthur L. Day and E. S. Shepherd, "Water and Volcanic Activity," *Bull Geol. Soc. Amer.*, Vol. XXIV (1912), p. 606.

[31] F. W. Clarke, "Date of Geochemistry," *U.S. Geol. Surv. Bull. 770* (1924), p. 261.

Whether or not part of the gases may have been of meteoric origin, it is important to note that they are a part of the magma at the time of extrusion and are not taken up from some lake into which the lava may have flowed.

The approximate percentage loss of water from a magma during solidification is thus explained by Day:[32]

> A silicate solution in its liquid state can take up water in solution in considerable quantity. A simple solution of silica and potash when heated under pressure in the laboratory is capable of taking up as much as 12.5 per cent of water in solution. A rock magma in the earth is just such a silicate solution, although more complicated in character, and is entirely competent to carry 5 or 6 per cent of water in solution under appropriate conditions. If it should happen that the lava beneath a volcano carries such quantities of water in solution, then all the phenomena of volcanism become appreciably clearer, for in the 8,000 or more analyses of crystalline rocks of igneous origin which have been gathered together by Washington and published by the United States Geological Survey [*Prof. Paper* 99] there is none containing more than 1½ per cent of water and less than 1 per cent is usual. This must mean that in the process of crystallization of the rock from the magma the water content is for the most part discharged.

From the time of extrusion until solidification, water vapor is given off in great quantities. If glass is developed, the process of crystallization is cut short; and the final solid may, therefore, contain more than the average amount of water found in igneous rocks. The vesicular and scoriaceous character of extrusive rocks is readily explained by the expansion and escape of contained gases.

All through his criticism Dr. Fuller emphasizes the large amount of steam generated by contact of the lava with surface water. He also stresses the idea of extensive hydration of the lava upon extrusion. When he states that a chemical analysis showed the water content to be "merely .30 of 1 per cent" he is emphasizing the smallness of the hydrous content of the solidified lava. That is quite a different matter.

In another place Dr. Fuller[33] states: "Field evidence indicates that the extensive hydration of the sideromelane to palagonite was due to the effect of the steam generated by the chilling of the lava and not to subsequent agencies." In that paper he also remarks that,

[32] "Some Causes of Volcanic Activity," *Smithsonian Rept. for 1925*, p. 264.

[33] "Concerning Basaltic Glass," *op. cit.*, p. 104.

"In the past this alteration has been attributed chiefly to later agencies," and cites a number of references to that effect. Then Dr. Fuller offers evidence to show that the alteration is syngenetic. He criticizes my paper as if his case of syngenetic alteration were a proved fact, which seems to be going farther than the evidence warrants. The fact that the lava is releasing magmatic water in the form of vapor at the time Dr. Fuller's hypothesis requires it to take up water is not considered.

The cooling effect of expanding gases is well known. As a mass of lava rises in a fracture or vent and then overflows, the pressures within the mass are greatly reduced. The result is that gases escape and the gas bubbles within the liquid expand. To form glass it is only necessary to reduce the temperature of the lava until the viscosity is great enough to prevent crystallization. Might it not be reasonable to assume that the cooling effect of the expanding gases in the vesicles is sufficient to line the walls with a very thin coating of glass? Dr. Fuller says that this effect is due to "exotic volatiles." It seems to me that he has quite a problem to show how the "exotic volatiles" were introduced against the pressures exerted by the escaping gases, or to show how the "exotic volatiles" were introduced even if there were no great internal gas pressures to overcome. A vesicular lava does not have the same structure as a porous sandstone.

The large quantities of gas present in lava have been indicated. The occurrence of spiracles or vertical gas vents might be explained by the escape of this gas from the lower part of a flow, moving downward to the contact at the base and then along the contact until it found an opening through which it could escape. It does not seem necessary to call upon the escape of steam, generated by contact of the hot lava with lake water, and imprisoned beneath the flow. Figure 13 in Dr. Fuller's article on Columbia River lava[34] shows a spiracle rising from the base of what appears, from the illustration, to be quite definitely a columnar flow. The gas vent is walled by basaltic columns. How can Dr. Fuller reconcile the existence of a spiracle in columnar basalt if it is to be explained by the escape of steam, imprisoned beneath the flow, which was generated by con-

[34] "Aqueous Chilling of Basaltic Lava on Columbia River Plateau," *op. cit.*, p. 299.

tact of the hot lava and surface water? If this flow were poured into a lake, why did it not shatter or become ellipsoidal?

Other factors considered by Dr. Fuller are the proximity of contemporary mountain ranges, the humid climate, and the rough and uneven surface. The rough and uneven surface which I referred to in my paper is the sort of billowy, hummocky, and channeled surface seen on the recent flows. If any ponds were present, they would certainly be small. The runoff from adjacent mountain ranges may supply water for lakes, but it does not necessarily follow that there were basins to be filled; nor can much weight be placed on the implication that because the climate was humid lakes existed in this area.

In accordance with the principles of viscous flow, a liquid sheet flowing over a solid surface is regarded as being composed of a series of innumerable layers. The bottom layer is stationary, and each succeeding overlying layer is considered as sliding over the layer below it. The upper layers must then be moving more rapidly than the lower layers. As the upper lava surface cooled a crust would form that would be carried along on the underlying, moving liquid. There would be some drag which would increase as the thickness of the crust increased. The most rapidly moving layers would not be in the central portion but some place above it, very near the top at first and then gradually falling as the drag of the overlying crust increased.

Dr. Fuller states that neither he nor Aaron C. Waters ever observed any of the dikes that play such an important part in my hypothesis. The color of the basalt dikes is very much like that of the surrounding basalt. They are not very distinct; yet I do not understand how it happens that neither of these observers recorded the presence of any dikes. My evidence for the dikes is both actual and implied. Not only did I see a number of dikes cutting the basalts, but the overlapping sheets in some of the flows[35] are so thin (10–30 feet and thinning to a few feet in places or even pinching out) that it is highly probable that the lines or points of eruption could not have been very far apart.

So much emphasis is placed by Dr. Fuller upon rapid chilling, which must occur as a result of contact of liquid lava with water,

[35] See figure in article by the writer, *op. cit.*, p. 187.

that he seems to overlook the fact that chilling by air can, and does, produce basaltic glass. Many careful observers in various parts of the world have noted the glassy coating on pahoehoe lavas. Pahoehoe lavas have many points in common with ellipsoidal basalts. In fact, so close is the resemblance that an ellipsoidal flow may be

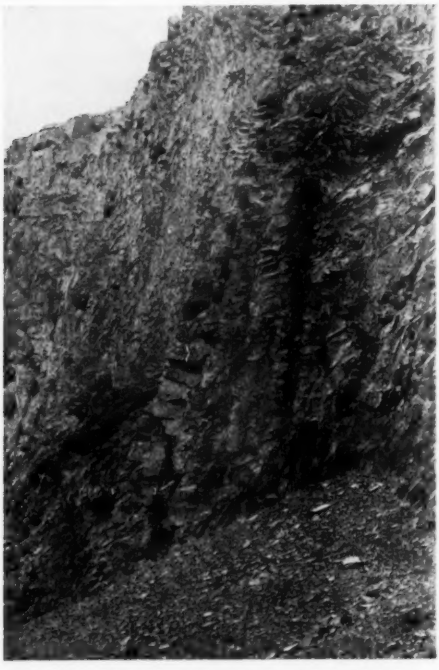

FIG. 5.—Basalt dike in basalt lava, east wall of Columbia River canyon, Rock Island, Washington. This exposure can be seen from main highway which is close by.

but a special case of pahoehoe. Dutton's[36] studies of the Hawaiian volcanoes led him to make the following observation:

> In a word, pahoehoe is formed by small offshoots of very hot and highly viscous lava from the main stream driven out laterally or in advance of it in a succession of small belches. These spread out very thin, cool quickly, and attain a stable form before they are covered by succeeding belches of the same sort.

[36] C. E. Dutton, "Hawaiian Volcanoes," *U.S. Geol. Surv. 4th. Ann. Rept.* (1884), p. 96.

The term "pahoehoe" was said by Dana[37] to mean "having a satin-like aspect," the satin-like aspect being due to the presence of a glassy coat. He further stated:

> The surface of the lava shows by the fine and coarse flow-lines over it, that it cooled as it flowed. Through one means and another the surface is usually uneven, being often wrinkled, twisted, ropy, billowy, hummocky, knobbed and often much fractured.

H. S. Washington,[38] under the heading, "Recent Lavas: Labradorite Basalt Glass Facies," made the following remark: "To this facies belong the numerous well-known glassy forms of the recent Kilauean lavas, such as the crusts of the pahoehoe flows." In speaking of the Vesuvius lavas, he[39] stated:

> The pahoehoe magma, by simmering in the throat of the volcano, has lost a large part of the vapor in solution in it, and issues thus with little internal mobility and consequent high viscosity, so that it cools rapidly from the surface inward and the viscosity increases rapidly to the point at which crystallization is no longer possible and the lava solidifies as a whole very largely as glass.

Referring again to Hawaiian rocks, Washington[40] has written:

> In pahoehoe there has been little crystallization, the greater part of which has taken place after the effusion of the lava, but solidification, or at least sufficient viscosity, has set in so early that molecular movement was checked or prevented and further crystallization has consequently been stopped. Although the pahoehoe lava has thus reached, soon after extrusion, a degree of viscosity sufficient to stop crystallization it yet remains a fluent and continuous mass, as is shown by the general movement of the flow, the flexibility of the crust, and the formation of the characteristic festooned and ropy surfaces and of the "toes" at the end of the stream.

Regarding the lava in Halemaumau, Day[41] has stated:

> The lowest temperature at which movement can be detected is therefore of the order of 600° C. A fragment of this same lava brought to the laboratory and reheated will not flow under its own weight until a temperature in the neighborhood of 1300° C. has been reached. Such an observation is significant of a change

[37] J. D. Dana, *Characteristics of Volcanoes* (1891), p. 9.

[38] H. S. Washington, *Petrology of the Hawaiian Islands*, Vol. III, "Kilauea and General Petrology of Hawaii," *Amer. Jour. Sci.*, Vol. VI (1923), p. 349.

[39] F. A. Perret, "The Vesuvius Eruption of 1906," *Carnegie Inst. of Wash. Mono.*, July, 1924; Washington, *Petrography of the Lavas of 1906*, p. 146.

[40] *Petrology of the Hawaiian Islands*, Vol. IV; "The Formation of Aa and Pahoehoe," *Amer. Jour. Sci.*, Vol. VI (1923), p. 417.

[41] "Some Causes of Volcanic Activity," *op. cit.*, p. 258.

of composition and yet the only change of composition possible must be in the amount of volatile matter (gas) in solution in it. Gases are given off in abundance during cooling and their loss takes away from the lava its fluidity over a considerable range of temperature.

Pahoehoe lavas have been observed on the crater floors of Vesuvius[42] and Kilauea,[43] as well as on their slopes. A photograph by Day and Shepherd[44] shows pahoehoe basalt on the surface of the liquid lava in the pit of Halemaumau. It is quite impossible to consider the glassy crusts on these basalts to have been formed by coming in contact with water.

T. A. Jaggar recently wrote[45] that the thickness of glass on the surface of pahoehoe basalt which has resulted from subaerial cooling is from $\frac{1}{8}$ inch to 3 inches thick. He further stated that he did not know of sea water chilling of pahoehoe, but that he would expect water chilling to form a very thin crust.

Many authoritative references might be cited, but the foregoing seem sufficient to show that the glassy selvages on basalt do not necessarily need the rapid chilling which may be produced by contact with water. Cooling by air is sufficiently rapid to form basaltic glass. It is necessary merely to reduce the temperature of the fluid to the point where it becomes too viscous to crystallize. This temperature might very probably be as high as 700° C., and range up to 900° C. or more, depending upon whether relatively much or little gas is associated with the lava.

[42] Perret, *op. cit.*, pp. 122–23.

[43] Dutton, *op. cit.*, p. 154; Dana, *op. cit.*, p. 114; H. A. Powers, *The Volcano Letter*, (Hawaiian Volcano Observatory, National Park, Hawaii), No. 348, Aug. 22, 1931.

[44] "Water and Volcanic Activity," *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), p. 581.

[45] Letter dated Dec. 10, 1933.

REVIEWS

Ore Deposits of the Western United States. Lindgren Volume, published by the American Institute of Mining and Metallurgical Engineers; sponsored by the Rocky Mountain Fund, 1933. Pp. 797; 63 figs. $6.50.

This volume constitutes unquestionably the most important American contribution within the field of ore deposits since the appearance of the first edition of Lindgren's *Mineral Deposits*. Its nearly eight hundred pages contain contributions from forty-four American economic geologists and the volume is dedicated to Waldemar Lindgren, leader of American economic geologists, in honor of nearly a half-century of active work in the field of economic geology. The volume is edited by a committee of which Dean John Wellington Finch, of the University of Idaho, is chairman. After a brief Foreword by George Otis Smith and the Preface, a section follows on the life and scientific work of Professor Lindgren, written with fine appreciation by Professor L. C. Graton, of Harvard, and closing with a classified list of Lindgren's writings.

Chapter I, by F. L. Ransome, is a historical review of geology as related to western mining, including a tracing of the development of concepts of ore genesis.

Chapter II, by G. F. Loughlin and C. H. Behre, Jr., on the classification of the ore deposits, is a commentary, class by class, of Lindgren's latest genetic classification as given in the fourth edition of his *Mineral Deposits*. The writers cogently point out the importance of wall-rock composition as a modifying factor in mesothermal ore deposition, especially in the case of calcareous versus siliceous rocks—a factor influencing not only the kind of ore deposition but probably also its speed. The structure and texture of the wall rocks are also important in determining the readiness with which mineralizing solutions can circulate and may spread mineralization thinly through a wide zone of declining temperature or concentrate it in a narrow zone in which earlier high-temperature minerals may be closely associated with later low-temperature minerals.

Chapter III, on the physical-chemical factors in the development of a deep-seated type of ore deposit, is one of fundamental importance in which Clarence N. Fenner, of the Geophysical Laboratory, discusses at

length the pneumatolytic processes in the formation of minerals and ores, considering primarily the means by which the metals sparsely scattered through the magma eventually become concentrated in aqueous mineralizing solutions.

In general, in the process of cooling, a possible separation of the magma into the following phases must be recognized:

1. A sulphide melt
2. Crystals of the common silicates and oxides
3. Gaseous emanations
4. Residual liquid which may eventually split because of limited immiscibility and which often becomes progressively richer in volatiles as crystallization proceeds

The majority of ore deposits are regarded as products of phases 3 and 4. As to which of these is dominant, opinions differ. To the residual liquids, or the gases evolved from them, or to combinations of both belong the pegmatites and certain ores related to pegmatite, such as tin and tungsten veins. But the majority of ore deposits, Fenner believes, are derived from the direct gaseous emanations and not from the residual liquids. In this he finds the reason for the absence of transitions from pegmatite to sulphide veins.

The data derived from the study of active vulcanism, particularly in Europe, are critically reviewed at some length to show the astonishing quantity of gas involved in many eruptions. Among the emanations chlorine compounds, notably HCl, are particularly abundant. Chlorides of base metals, particularly ferric chloride, are common, and it is deemed probable that chlorides are the most important form of combination in which the metals are sublimated from the emanations. The surface in the vicinity of Vesuvius has been whitened with sodium chloride for several days after certain eruptions.

Evidence is cited to show that not only chlorides but also oxides of the metals, including SiO_2 and a great variety of silicates, may be deposited from gaseous solutions and that such deposits may be indistinguishable from hydrothermal deposits of the same minerals.

In Part II of this chapter the broader story of the magmatic differentiation is briefly told by N. L. Bowen, of the Geophysical Laboratory. After emphasizing the view, developed particularly by Harker, that magmatic differentiation does not proceed to any important degree in the wholly liquid state but *pari passu* with crystallization, Bowen proceeds to a discussion of the fractional crystallization of magmas, stressing the parallelism in mineral composition between the sequence of rocks developing in differentiation and the normal order of crystallization in individual

igneous rocks. Both are simply a manifestation of the changing composition of the residual magmas resulting from the subtraction of crystals. The more fusible or "hyperfusible" components tend to become concentrated in the residual liquid. These include the more volatile components, notably water, but also some that are not highly volatile, such as tungstates and molybdates. In general, the greatest concentrations of hyperfusible components occur in acid rather than basic magmas.

The residual liquids are probably alkaline; they constitute the pegmatite magmas. Under certain conditions, boiling of the pegmatitic residual magma is believed to occur, e.g., the formation of a gaseous phase. This happens not as a consequence of a rising temperature but in spite of declining temperature and is due to crystallization and consequent increased vapor pressure in the remaining liquid. The gases produced by this boiling process are believed to be acid due mainly to the abundance of HCl. They are regarded by Bowen as the principal source of the mineralizing waters. They react vigorously with calcareous rocks but only feebly with silicate rocks. But as they move farther out into cooler surroundings and condense to liquid, they may then react vigorously with all classes of wall rocks and their acidity becomes neutralized.

Thus Bowen connects the commoner procedure of mineralization with the boiling of pegmatite magmas, whereas Fenner attributes only a few ores, such as tin and tungsten, to this source and considers that the majority were condensed from gases given off directly from the parent-magma.

In Part III of this chapter Clarence S. Ross discusses differentiation as a source of ore-forming materials in the ore deposits of the Ducktown type occurring in the Appalachian region. Part IV of the chapter, by W. T. Schaller, is devoted to pegmatites.

Chapter IV is a discussion by Waldemar Lindgren of the fundamental causes of mineralization in the Cordilleran region. At the end of the Jurassic, impulses originating in the Pacific segment began to effect compression and folding and great batholithic intrusions began forming, the largest being the great coast batholith extending from Lower California to Alaska. Mineralization accompanied these intrusions.

The intrusive action gradually spread eastward and by Eocene times had reached the eastern margin of the Cordilleran region, as, for example, the Black Hills. Regional uplift accompanied the intrusions, and with the eastward spread of the intrusions there was a consistent change in the composition of the magmas from dominantly diorite, granodiorite, and quartz monzonite in the Pacific Coast region to alkaline types on the eastern limits of the area. With this change in general composition was an

increase in the volatile content of the magmas of which the fluorite content of the associated ore deposits forms an index.

With respect to the mechanism of this large-scale process of magmatic differentiation, Lindgren states:

> It is realized that this suggested liquid differentiation does not agree with the orthodox theory of fractional crystallization and reaction series. These modes of differentiation have their place and their importance cannot be denied, but it is held that they can scarcely be expected wholly to explain differentiation in exceedingly deep and exceedingly hot magma basins. During the differentiation vast quantities of volatiles were set free, some being retained by the lavas, but the bulk not released until after the close of the effusive epoch.

Chapter V, "The Hydrothermal Depth-Zones."—In this chapter Professor L. C. Graton, of Harvard, gives an excellent discussion of the classification of hydrothermal ore deposits originally developed by Lindgren in the light of later accessions of knowledge of ore occurrence, particularly at considerable depths. The vertical span of hypothermal or deep-seated conditions of hydrothermal mineralization, he considers, may not uncommonly be as much as 5 miles. Contact metamorphic deposits he regards as special phases of hypothermal mineralization conditioned by the presence of carbonate wall rocks.

Between the mesothermal and the epithermal zones, as defined by Lindgren, Graton would recognize a leptothermal zone.

The term "telethermal" proposed by Doll is used by Graton to indicate the enfeebled effects of hydrothermal solutions in relatively cool rocks far from the igneous sources. The lead and zinc deposits of the Mississippi Valley are regarded by him as types of this class. There would seem to be good justification for this category, which presents some marked contrasts to such typically epithermal deposits as, for example, most cinnabar deposits, particularly in coarser texture and absence of hydrothermal alteration beyond the actual ore deposit. The category seems justified in spite of the obvious difficulties in distinguishing such deposits from those formed by meteoric waters remote from their sources, but extreme caution is advisable in a diagnosis of the telethermal class.

Chapter VI.—In the first part of this chapter B. S. Butler presents the most general features of the stratigraphy and structure of the Cordilleran region in their relation to igneous activity and mineralization and in Part II other authors—Hulin, Waters, Clyde P. Ross, Burbank, Lovering, and Harrison Schmitt—present in more detail the characteristics of certain parts of the region. This important chapter is itself a summary and does not lend itself to further summarization, but it contains an immense

amount of material important for an understanding of the conditions of ore deposition in particular parts of the region.

Chapter VII.—In this chapter W. H. Emmons discusses the mechanism of the deposition of certain metalliferous lode systems associated with granitic batholiths. Probably 95 per cent of the ore deposits associated with igneous rocks are connected with acid rather than with basic intrusives. In considering the relation of ore deposits to batholiths, the term "roof" is applied to the covering of older rocks and the term "hood" to the outer and first solidified portion of the intrusive. The ore deposition is largely confined to the roof and the hood. The portions of the intrusive lying deeper than the hood are commonly barren of valuable ores, though pegmatite and valueless quartz veins may occur. The lower limit of the hood constitutes the "dead line" or limit of metallization.

Vein fracture in roof and hood often parallel roughly the long axes of the intrusive and are thought in such cases to be due in part at least to vapor pressure resulting from crystallization deeper within the batholith.

Chapter VIII.—In this chapter Professor A. F. Buddington, of Princeton attacks the difficult problem of the correlation of kinds of igneous rocks with kinds of mineralization. The criteria available in establishing such relations are first considered. After indicating the complexities and uncertainties involved, the various classes of igneous rocks are discussed seriatim with reference to their ore associates.

Chapter IX.—In this chapter W. H. Emmons reviews the recent progress in the studies of supergene enrichment. The lateritic ores of iron, manganese, and aluminum that are believed to be products of rock weathering under tropical conditions are first considered. In the formation of some of these, bacteria may have played an important rôle. Attention is directed to the development of supergene magnetite and martite close to the surface in the lateritic iron ores of eastern Cuba and other localities. In the iron ores of Mesabi, however, where the magnetite and its alteration product, martite, are the principal minerals, they have been regarded by Gruner, because of their abundance, as hydrothermal. Downward sulphide enrichment is considered with respect to copper, silver, gold, zinc, lead, and nickel.

Chapter X is devoted to sedimentary deposits. Part I is a review by J. T. Pardee of existing knowledge of the placer deposits of the Western United States. Part II, by Frank L. Hess, of the United States Bureau of Mines, deals with the occurrences of uranium, vanadium, radium, gold, silver, and molybdenum in sedimentary deposits. The uranium and vanadium deposits of southwestern Colorado and Utah in Triassic and

Cretaceous sandstones are discussed at length. The present minerals are all oxidized products and the nature of the original mineral is uncertain. In many of the deposits the association of ores with fossil-plant remains is very close and two logs in one ore deposit yielded ore valued at $233,000. In general, the silver, uranium, and vanadium deposits of this class are believed to have been laid down in very shallow lakes, the metals having been derived in solution from veins in neighboring highlands and organic matter functioning as a precipitating agent. The greatest difficulty in a diagnosis of these deposits has always been the finding of an adequate source for such large amounts of rare metals.

In Part III, John Wellington Finch deals in concise fashion with the sedimentary copper deposits of the Western United States. Copper from the bordering highlands was deposited with the Red Beds sediments in part from solution and in part mechanically as copper-bearing fragments. With burial under later deposits, the copper was redistributed by ground waters and concentrated under reducing conditions in and around inorganic material. Later erosion and exposure to oxidation brought the deposits to their present state with wide scattering of oxidized copper minerals.

In Parts IV, V, and VI the sedimentary manganese deposits are briefly described by D. F. Hewett and the phosphate and potash deposits by G. R. Mansfield.

Chapter XI.—In one of the longest chapters, about one hundred and eighty pages, the principal ore deposits of the Western United States are classified and discussed in accordance with Lindgren's genetic classification, nineteen authors, under the leadership of J. T. Singewald, Jr., participating in this work. The chapter constitutes a most useful review of present knowledge.

Chapter XII.—This chapter, dealing with the utilization of geology by mining companies, is written by geologists of large experience in the systematic application of science to mining. General considerations are discussed by D. H. McLaughlin and Reno H. Sales; methods at Butte are treated by F. A. Linforth, of the Anaconda Company; Cananea methods by V. D. Perry, chief geologist, Cananea Copper Company; the Old Dominion Mine, Globe, Arizona, by G. N. Bjorge and A. H. Shoemaker; Tintic by Paul Billingsley; and Homestake by D. H. McLaughlin.

Chapter XIII, on the history and influence of mining in the Western United States, is by Charles W. Henderson.

EDSON S. BASTIN

Textbook of Geology, Part II: *Historical Geology*. By CHARLES SCHUCHERT and CARL O. DUNBAR. 3d ed. New York: John Wiley & Sons, 1933. Pp. 551; pls. 35; figs. 332. $4.00.

From the sidelines it has been interesting to watch the metamorphosis of that fine old Yale textbook team of Pirsson and Schuchert. On the physical side Longwell, Knopf, and Flint have now been in the line-up in place of Pirsson for some time; and recently a new man, Carl Dunbar, has been added to the historical roster. Judging from the results, it is safe to say that the new men can play the game quite as well as their elders. Of course, one does not have to read far in the present historical text to see that the veteran Schuchert is still captain, yet nevertheless there is readily discernible a new attack which is at least in part attributable to his new team mate.

The truth of the matter is that this edition has been so thoroughly rearranged, added to, and subtracted from that it is now in fact, as well as in name, a textbook. The earlier editions, although widely used and extremely valuable, were generally considered rather hard to teach, chiefly because they were actually Schuchert's elaborated notes on historical geology rather than true textbooks of the subject. But in spite of the fact that the treatment has been unified and improved, the authoritative character of the older editions has not been lost. In them first appeared not only many a new idea, but also a multitude of new names for old processes, principles, and periods of orogeny. The new edition is similarly crammed with thought-provoking suggestions and generalizations, as well as a further-expanded nomenclature.

Midwesterners may, however, detect an eastern aura in some of the text treatments of both formations and theories. There actually may be a slight tendency to describe eastern areas and formations more fully than western ones. But certainly in large part this can be explained by the ready availability and greater knowledge of the data concerning the eastern sections. Indeed, to the reviewer the work seems rather well balanced in respect to the treatment of critical areas regardless of geographic location. In the consideration of the theories of earth origin, however, there is a pretty definite case of eyes turned eastward. This may be seen in the discussion of the Jeans-Jeffreys tidal theory, which for the first time is rather fully outlined in an American text on geology. But, unfortunately, objections, so fully expressed for the Laplacian and Chamberlin-Moulton theories, apparently do not exist for the English variation of the American parent.

The book is copiously illustrated with new plates, figures, and paleogeographic maps. The tables of formations also have been greatly expanded and brought in accord with the most recent concepts of correlation. The text emphasizes principles of interpretation, and avoids, so far as is possible in a work of this sort, a deadly encyclopedic cataloguing of facts. Dressed up on the outside with a more attractive binding, and refreshed within by a literary style which should be more appealing to the students, this new text probably will live up to the many good things which are heard about it in the current geologic gossip.

CAREY CRONEIS

Transactions of the American Institute of Mining and Metallurgical Engineers. Geophysical Prospecting, 1932. New York: American Institute of Mining and Metallurgical Engineers, 1932. Pp. 510.

This is the second of a series of volumes published by the American Institute of Mining and Metallurgical Engineers on geophysical prospecting. It contains papers and discussions presented at the meetings of the Institute from 1929 to 1932. Although this volume includes papers treating many phases of geophysical prospecting, those devoted to electrical methods are most numerous. Of special interest to geologists are contributions on the choice of geophysical methods, by E. De Golyer, and a general summary of results achieved in different areas, by D. H. McLaughlin, A. M. Bateman, and others. The remaining contributions, because of more detailed treatment, are of interest principally to specialists.

H. W. STRALEY, III

"*Die Feldspäte und ihre praktische Bestimmung.*" By KARL CHUDOBA. Stuttgart: Schweizerbart, 1932. Pp. 54; figs. 46; pls. 4. M. 6 (bound).

After a brief description (12 pages) of chemical, morphological, and optical properties the remainder of this pamphlet is given over to determinative methods using thin sections under the polarizing microscope either with (19 pages) or without (17 pages) the universal stage. The object is to furnish a brief but critical outline of those methods of feldspar determination which seem to be most advantageous for the "practical working petrographer and geologist."

D. J. F.